AD-A238 215

:NTATION PAGE

Form Approved
OMB No. 0704-0188

2

...ORT DATE: 21 June 1991	3. REPORT TYPE AND DATES COVERED: Final, 20 Sept 90 - 21 June 91
4. TITLE AND SUBTITLE: Side Information in Spread-Spectrum Packet Radio Networks	5. FUNDING NUMBERS: DAAL03-90-C-0027
6. AUTHOR(S): H. B. Russell and M. B. Pursley	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES): Techno-Sciences, Inc. 7833 Walker Drive, Suite 620 Greenbelt, MD 20770	8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES): U. S. Army Research Office P. O. Box 12211 Research Triangle Park, NC 27709-2211	10. SPONSORING/MONITORING AGENCY REPORT NUMBER: ARO 27982.1-EL-SBI

11. SUPPLEMENTARY NOTES

The view, opinions and/or findings contained in this report are those of the author(s) and should not be construed as an official Department of the Army position, policy, or decision, unless so designated by other documentation.

12a. DISTRIBUTION/AVAILABILITY STATEMENT: Approved for public release; distribution unlimited.	12b. DISTRIBUTION CODE

13. ABSTRACT (*Maximum 200 words*)

Reliable data distribution within spread-spectrum packet radio networks requires high performance from the communication links and the network protocols. Side information can be extracted from received signals that are embedded in noise and interference, and this information can be used to improve the quality of the links and to aid the network protocols in establishing reliable routes in the network. We have carried out the design, development, and evaluation of techniques and algorithms for developing side information and using it effectively to aid link and network performance in spread-spectrum packet radio networks. We have found that reliable side information can be obtained from the demodulator and decoder in the radio receiver, and that it can be used effectively on the links and in the network protocols to improve the overall performance of the radio network.

14. SUBJECT TERMS: Side information, spread spectrum, radio networks, network protocols	15. NUMBER OF PAGES: 53
	16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
UNCLASSIFIED	UNCLASSIFIED	UNCLASSIFIED	UL

NSN 7540-01-280-5500

Standard Form 298 (Rev 2-89)
Prescribed by ANSI Std Z39-18
298-102

FINAL REPORT

Side Information in Spread-Spectrum Packet Radio Networks

prepared by

M. B. Pursley and H. B. Russell

Techno-Sciences, Inc.
1776 E. Washington
Urbana, IL 61801

A-1

ABSTRACT

Reliable data distribution within spread-spectrum packet radio networks requires high performance from the communication links and the network protocols. Side information can be extracted from received signals that are embedded in noise and interference, and this information can be used to improve the quality of the links and to aid the network protocols in establishing reliable routes in the network. We have carried out the design, development, and evaluation of techniques and algorithms for developing side information and using it effectively to aid link and network performance in spread-spectrum packet radio networks. We have found that reliable side information can be obtained from the demodulator and decoder in the radio receiver, and that it can be used effectively on the links and in the network protocols to improve the overall performance of the radio network.

The research described in the report was supported by the U.S. Army Research Office under Contract Number DAAL03-90-C-0027. The views and conclusions in this document are those of the authors and should not be interpreted as representing the official policies, either expressed or implied, of the U.S. Army Research Office or the U.S. Government.

1. SIDE INFORMATION IN FH PACKET RADIOS

Spread-spectrum packet radio networks are needed for Army battlefield communication and data distribution, and these networks are likely to be subjected to severe interference from jamming, multiple-access interference, and RFI from narrowband emitters. Reliable data distribution within these networks requires not only good performance from the elements that make up the individual links but also good performance from the network protocols that are needed to provide a survivable network.

Side information can be extracted from received signals that are embedded in noise and interference. This side information can be used to improve the link quality and also to aid the network protocols. The problem is to design, develop, and determine the performance of techniques and algorithms for generating side information and using it effectively to aid link and network performance in spread-spectrum packet radio networks.

The goal of the subsystem that generates side information is to detect unreliable symbols. In the context of the multiple-access application, this amounts to erasing some of the symbols that have been hit by interference due to other frequency-hop radios, particularly those for which the interference is excessive. The packet error probability is decreased greatly if such symbols can be detected and erased [16]. For strong tone or multiple-tone jamming, it is usually the case that all symbols with interference should be erased. For more noise-like interference, such as that caused by partial-band noise jamming, the situation is less clear. Symbols having interference are not necessarily erased.

The *received signal* at a terminal in a frequency-hop radio network consists of the desired signal, other frequency-hop signals, interference, and wideband noise. We focus on the reception of the desired signal during a particular dwell interval, and any other frequency-hop signals that happen to occupy the same frequency band during any portion of the dwell interval are considered as multiple-access interference. From the point of view of the receiver for the desired signal, the interference from a single frequency-hop radio produces block interference (i.e., it affects a block or sequence of symbols that were transmitted in that dwell interval). In particular,

the interference from any frequency-hop radio with a dwell interval at least as long as that of the desired signal, regardless of whether it is slow or fast hopping, produces block interference that either begins with the first symbol in the dwell interval or ends with the last. If it is known that multiple-access interference is present in a dwell interval, a sequence of successive symbols at the beginning or the end of the dwell interval should be erased. If the time offset between the dwell interval of the desired signal and that of the interference is not known accurately, it is usually wise to erase all symbols in the dwell interval of the desired signal.

As indicated above, the situation is more complicated for partial-band noise jamming. The decision to erase or not erase a symbol with interference due to noise jamming depends on the noise density level for the jammer. Optimal decision rules have been formulated to determine when to erase symbols received over a channel with pulsed or partial-band noise jamming [1]. In the discussion that follows, we will simplify the situation by considering only very strong interference, in which case the optimal decision is to erase all symbols with interference, provided the total number of erasures does not exceed the erasure correcting capability of the code.

There are several classes of methods for generation of side information in a frequency-hop radio network. These can be divided into three general categories: predetection, postdetection, and network-based methods [9]. Included in the *predetection* category are methods based on power measurements applied to the received signal *during* the dwell interval and energy detection based on segments of the received signal in dwell intervals immediately *prior to* and *following* the dwell interval of interest. The former methods attempt to distinguish between two hypotheses: (1) interference absent and (2) interference present. For the power measurements within the dwell interval, these two hypotheses correspond to a (1) a single frequency-hop signal is present and (2) either two or more such signals are present or one such signal and strong interference are present. If energy detection is applied outside the dwell interval — and this is appropriate only when each frequency hop pattern is not allowed to use the same frequency in two or more consecutive dwell intervals — the goal is to determine if there is

interference present outside the dwell interval (note that the desired signal is not present there). Each of these predetection techniques is channelized in the sense that the frequency band in which the measurement is made corresponds to the frequency slot occupied by the signal of interest, and the test is applied on a hop-by-hop basis.

The power measurements might be accomplished by using outputs from an AGC device, and the energy detection can be performed by a radiometer. In the first of these predetection methods, the idea is that if a single signal is present and there is no interference, the power should be less than if interference is present. In the second method, the idea is to check for residual energy in the frequency slot both before and after the dwell interval of the desired signal. Because of the asynchronism between the radios in the network, hits by other radios will, with high probability, produce energy outside the dwell interval. For typical radios, predetection methods are the least reliable of the methods we have considered, in part due to their sensitivity to fluctuations in the attenuation of the channel, the gain of the receiver front-end (RF section), and the transmitted power levels.

Postdetection methods are based on certain statistics obtained from the outputs of the demodulator. For binary FSK signaling with noncoherent detection, the statistics might be the outputs of the two noncoherent matched filters (e.g., envelope detectors) at the appropriate sampling instant. In the absence of interference, we expect only one of these to be large, since the input to the other is the thermal noise only. If both outputs are large, it is reasonable to assume that two or more signals are present in the receiver input. Clearly, postdetection methods which have been proposed for used in anti-jam communication, such as Viterbi's ratio threshold technique [17], are suitable for use in a multiple-access application as well. In fact, such methods (perhaps with some modifications) will typically be even more effective against multiple-access interference than against jamming because of the fact that, for multiple-access interference, the interference waveforms are known completely to the receiver.

If we include in the transmitted signal a known sequence of symbols in each dwell interval, the implementation of postdetection side information generation is simpler and the

performance is improved in most cases. The number of symbols that are received correctly for a given dwell interval can be used as a statistic upon which to base the decision regarding the reliability of the data symbols in that dwell interval. This method, which is employed in [9], can be made arbitrarily reliable by increasing the number of symbols in the sequence. Of course, an increase in the number of side information symbols produces a decrease in the information rate, so a tradeoff can be carried out to maximize the information throughput subject to the constraints on the error probability [10].

Network-based methods require the radios to obtain additional information from their neighbors in the network, and of course they deal with the multiple-access interference only. By neighbors we mean radios which are within range and are therefore potential sources of interference. Perhaps the most important example arises in systems in which the radios can track multiple hopping patterns. By tracking the hopping patterns of all of its neighbors, a radio knows in advance that a hit will or will not take place. In this situation, the radio can actually erase data symbols before they arrive. If the hopping patterns are tracked perfectly, this method produces perfect side information, and hence the results of [8] apply. In general, however, there are many cases in which the radio may not be able to track the hopping patterns of all of its neighbors (e.g., because of hardware limitations or due to a highly dynamic network topology), and the side information will be imperfect. Of course, when partial-band jamming is present, the side information is always imperfect.

The development and application of side information in frequency-hop (FH) packet radio networks has been investigated during Phase I. In the remainder of Section 1, various methods for obtaining side information are assessed, and it is determined that a scheme utilizing test symbols is the most appropriate for this study of Army packet radio networks, particularly mobile frequency-hop radio networks. In Section 2, the link and the network protocols are enhanced to use the side information, and the techniques are tested in our frequency-hop packet radio network simulation that not only simulates the frequency-hop radios but also permits inclusion of mobile sources of partial-band interference.

1.1 Methods for obtaining side information

During the Phase I investigation we have concentrated our efforts on postdetection side information methods. The predetection methods depend much more heavily on the assumptions concerning the channel, gain of the receiver, and power levels, and satisfactory models have not been developed; furthermore, predetection methods give less reliable side information. The network methods depend on coordination within the network, and we do not believe that they will be as suitable for Army mobile radio network applications. Furthermore, these methods do not help against jamming; in fact they are designed only for multiple-access interference.

There has been a great deal of research at the link level on postdetection methods for obtaining side information [1-3,6,9,10,17]. In our Phase I project, three methods for generating side information have been examined in detail. The goal of the first method is to determine if partial-band interference is present within a particular dwell interval and, if so, to erase the entire dwell interval. Side information that is oriented toward providing a reliability measure for an entire dwell interval is referred to as *dwell interval side information.* One example of dwell interval side information is that obtained from test symbols [9]. The second method we have examined, called *symbol side information*, detects partial-band interference and makes erasures on a symbol-by-symbol basis. The ratio-threshold test can be used to obtain of symbol side information [1]. A third, hybrid scheme combines the techniques of the first two methods. Erasures are made on a symbol-by-symbol basis but when too many symbols have been erased in a particular dwell interval, the entire dwell interval is erased. An example of this method is the parity test symbol scheme [6]. We have assumed that binary, orthogonal, equal-energy signaling is used with optimal noncoherent detection at the receiver.

The dwell interval side information scheme considered here is taken from [9,10]. In each dwell interval are included N test symbols from a known sequence and the symbols are examined as one or two groups. The receiver examines the received test symbols of a group in a particular dwell interval, and if more than γ test symbols are in error, all the data symbols in the dwell

interval are erased. Notice that when there are two groups, if either group has more than γ errors, the entire dwell interval is erased.

The symbol side information scheme considered here is based on [1-3,17], and no test symbols are used. The receiver compares the outputs of the two envelope detectors for each binary symbol. If the ratio of the smallest to the largest output is greater than θ, the symbol is erased.

A third scheme for the generation of side information, given in [6], uses parity binary symbols as the test symbols. Appended to each code symbol is a binary parity symbol. The receiver calculates the parity for a received code symbol and if it does not match the received parity symbol, the code symbol is erased. If more than γ code symbols are erased in a dwell interval, the entire dwell interval is erased.

1.2 Calculation of packet error probability

The calculation of the probability that a packet can be decoded when there is *both* partial-band and multiple-access interference present is developed as an extension to results given in [9]. The method of calculation is to condition on the type of interference present in each dwell interval, then condition on the number of erasures for each type of interference, and finally to condition on the number of errors given the type of interference and that there has not been an erasure. This conditioning yields the number of errors and erasures for each codeword in a packet, and a codeword can be decoded if there are not too many errors and erasures. First, we present the calculation for the probability that a packet can be decoded when using the test symbol side information scheme (i.e., when a decision to erase has been made, the entire dwell interval is erased). A simple modification also provides the probability that a packet can be decoded when a symbol side information scheme is used.

The standard frequency hopping model is used here [7,8]. In particular, the probability a dwell interval is hit, P_h, is upper bounded by $2/q$ where q is the number of frequency slots, and the hits between successive dwell intervals are assumed to be independent. A certain number of

the frequency slots are subjected to the partial-band interference which occupies a fraction ρ of the band. One can interpret ρ as the probability that a particular frequency slot contains partial-band interference.

A packet contains of L codewords with each codeword consisting of n symbols from a (n,k) Reed-Solomon code, and the codewords are fully interleaved [8]. A dwell interval is said to be hit if either partial-band or multiple-access interference is present in the dwell interval.

The first step in calculating the probability a packet can be decoded is to condition on the possible types of interference that may be present in each dwell interval. Let a be the number of dwell intervals that are hit by multiple-access interference. The probability that a packet can be correctly decoded is

$$\Pr(\text{packet decoded}) = \sum_{a=0}^{n} \Pr(a \text{ hit}) \Pr(\text{decode} \mid a),$$

where the probability that a dwell intervals are hit by multiple-access interference is

$$\Pr(a \text{ hit}) = \binom{n}{a} P_h{}^a (1 - P_h)^{n-a}.$$

Of the a dwell intervals that are hit by multiple-access interference, let b denote the number of these that are also hit by partial-band interference. Also, of the $n-a$ dwell intervals that are not hit by multiple-access interference, let c denote the number of these that are hit by partial-band interference only. Conditioning first on b, the conditional probability a packet can be decoded given a is

$$\Pr(\text{decode} \mid a) = \sum_{b=0}^{a} \Pr(b \text{ hit}) \Pr(\text{decode} \mid a,b),$$

where the probability that b of the a dwell intervals are hit by partial-band interference is

$$\Pr(b \text{ hit}) = \binom{a}{b} \rho^b (1 - \rho)^{a-b}.$$

Conditioning on c, the conditional probability a packet can be decoded given a and b is

$$\Pr(\text{decode}|a,b) = \sum_{c=0}^{n-a} \Pr(c \text{ hit}) \Pr(\text{decode} \mid a,b,c), \tag{1}$$

where

$$\Pr(c \text{ hit}) = \binom{n-a}{c} \rho^c (1-\rho)^{n-a-c}.$$

This partitions the dwell intervals into four groups: 1) those hit by both multiple-access (MA) and partial-band interference, 2) those hit by MA interference only, 3) those hit by partial-band interference only, and 4) those not hit. For each of these dwell intervals the decision to erase depends on the number of test symbols that are received in error. Given the type of interference present, the events corresponding to different dwell intervals being erased are independent. Table 1 summarizes the number of dwell intervals that are subject to a particular type of interference and the probability that a dwell interval is erased given the type of interference that is present. The locations of the test symbols within the dwell interval and whether the test symbols are tested as one group or separated and tested as two groups affects the calculation of the probability a packet can be decoded through the erasure (and error) probabilities only. The particular implementation of the test symbol scheme is accounted for in the calculation of the erasures probabilities.

Table 1. Probability a dwell interval is erased

Type of interference	Number of dwell intervals	Probability of erasure
both	b	β_3
MA	$a-b$	β_2
jamming	c	β_1
quiescent	$n-a-c$	α

The next step in calculating the probability that a packet can be decoded is to condition on the number of dwell intervals that are erased when subject to one of the four types of interference environments. For the b dwell intervals that have both multiple-access and partial-band interference present, let d denote the number of them that are erased. Conditioning on d,

$$\Pr(\text{decode}|a,b,c) = \sum_{d=0}^{b} \binom{b}{d} \beta_3{}^d (1-\beta_3)^{b-d} \Pr(\text{decode } |a,b,c,d).$$

For the a–b dwell intervals that have only multiple-access interference present, let e denote the number that are erased. Conditioning on e,

$$\Pr(\text{decode}|a,b,c,d) = \sum_{e=0}^{a-b} \binom{a-b}{e} \beta_2{}^e (1-\beta_2)^{a-b-e} \Pr(\text{decode } |a,b,c,d,e).$$

For the c dwell intervals that have only partial-band interference present, let f denote the number that are erased. Conditioning on f,

$$\Pr(\text{decode}|a,b,c,d,e) = \sum_{f=0}^{c} \binom{c}{f} \beta_1{}^f (1-\beta_1)^{c-f} \Pr(\text{decode } |a,b,c,d,e,f) .$$

Finally, for the n–a–c dwell intervals that have neither multiple-access nor partial-band interference present and only quiescent noise is present, let g denote the number that are erased. Conditioning on g,

$$\Pr(\text{decode}|a,b,c,d,e,f) = \sum_{g=0}^{n-a-c} \binom{n-a-c}{g} \alpha^g (1-\alpha)^{n-a-c-g} \Pr(\text{decode } |a,b,c,d,e,f,g) .$$

We say an *undetected hit* occurs when a dwell interval is hit by multiple-access or partial-band interference but is not erased. Since the L codewords of a packet are fully interleaved (i.e., the m-th symbol of each codeword is transmitted in the m-th dwell interval), an undetected hit or erasure in the m-th symbol of one codeword implies a undetected hit or erasure, respectively, for the m-th symbol of all L codewords. However, the errors from either the multiple-access or partial-band interference or wide-band noise are conditionally independent given the locations of the undetected hits and erasures. So the conditional probability that the packet can be decoded is

$$\Pr(\text{decode packet } | \ a,b,c,d,e,f,g) = \Pr(\text{decode codeword } |a,b,c,d,e,f,g)^L . \tag{2}$$

The final step is to condition on the number of symbols that are in error given the number of symbols that are subjected to a particular type of interference and have not been erased. Table 2 lists the four types of interference that may be present and the number of dwell intervals that

have that type of interference but that are not erased. Also listed is the probability that a symbol is in error given the type of interference and that the symbol has not been erased.

Table 2. Probability a symbol is in error.

Type of interference	Number of dwell intervals	Probability of error
both	$b-d$	p_3
MA	$a-b-e$	p_2
jamming	$c-f$	p_1
quiescent	$n-a-c-g$	p_0

For the $b-d$ symbols of a particular codeword that have both multiple-access and partial-band interference present, let h denote the number of symbols that are in error. Conditioning on h, the conditional probability a codeword can be decoded is

$$\Pr(\text{decode}|a,b,c,d,e,f,g) = \sum_{h=0}^{b-d} \binom{b-d}{h} p_3{}^h (1-p_3)^{b-d-h} \Pr(\text{decode }|a,b,c,d,e,f,g,h) \ .$$

For the $a-b-e$ symbols of a particular codeword that have only multiple-access interference present, let i denote the number of symbols that are in error. Conditioning on i, the conditional probability a codeword can be decoded is

$$\Pr(\text{decode}|a,b,c,d,e,f,g,h) = \sum_{i=0}^{a-b-e} \binom{a-b-e}{i} p_2{}^i (1-p_2)^{a-b-e-i} \Pr(\text{decode }|a,b,c,d,e,f,g,h,i) \ .$$

For the $c-f$ symbols of a particular codeword that have only partial-band interference present, let j denote the number of symbols that are in error. Conditioning on j, the conditional probability a codeword can be decoded is

$$\Pr(\text{decode}|a,b,c,d,e,f,g,h,i) = \sum_{j=0}^{c-f} \binom{c-f}{j} p_1{}^j (1-p_1)^{c-f-j} \Pr(\text{decode }|a,b,c,d,e,f,g,h,i,j) \ .$$

Finally, of the $n-a-c-g$ symbols of a particular codeword that have only wide band noise present, let l denote the number that are in error. Conditioning on l, the conditional probability a codeword can be decoded is

$$\Pr(\text{decode}|a,b,c,d,e,f,g,h,i,j) = \sum_{l=0}^{n-a-c-g} \binom{n-a-c-g}{l} p_0{}^l (1-p_0)^{n-a-c-g-l}$$
$$\times \Pr(\text{decode } | a,b,c,d,e,f,g,h,i,j,l).$$

A particular codeword can be decoded if the number of erasures plus twice the number of errors is within the error correcting capability of the code. So, the conditional probability a codeword can be decoded given the number of errors and erasures is

$$\Pr(\text{decode } | a,b,c,d,e,f,g,h,i,j,l) = \begin{cases} 1 & \text{if } d+e+f+g+2(h+i+j+l) \le n-k \\ 0 & \text{otherwise} \end{cases}.$$

A simple modification is all that is need to make the above calculation correct when symbol side information is employed (i.e., decisions to erasure occur independently from symbol to symbol). In calculating the probability that a packet can be decoded while using test symbols, we conditioned on all the events that are identical for all codewords in the packet (namely, the type of interference that is present in each dwell interval and the number of dwell intervals that are erased). With this conditioning, events corresponding to correct decoding of different codewords are independent, so the probability the packet can be decoded is the the L-th power of the conditional probability that a codeword can be decoded. When using symbol side information the events that are the same for all codewords are conditioned on as before, which in this case is only the type of interference present in each dwell interval since the symbols are erased on a symbol-by-symbol basis. The errors and erasures are made independently for each symbol in a dwell interval, thus the errors and erasures for different codewords are independent. So, instead of raising the conditional probability that a codeword can be decoded to the L-th power in (2), the Pr(decode | a,b,c) should be raised to the L-th power in (1).

Also, the conditional probabilities listed in Table 1 are redefined to be the probability that a particular symbol is erased given the type of interference present. The error probabilities listed in Table 2 are not changed. Recall that these are the probabilities that a symbol is in error given the type of interference present and that the symbol has not been erased.

For the parity test symbol scheme with $\gamma=0$, entire dwell intervals are erased, and the scheme can be analyzed as a dwell interval side information scheme. If $\gamma=L$, only individual symbols are erased, and the scheme can be analyzed as a symbol side information scheme. But, for other values of γ, a dwell interval that is not erased may contain some symbols that are erased. We have determined the packet error probability only when γ is one of these two extreme values. The analysis given in [6] for the parity test symbol scheme assumes that multiple-access interference is the primary type of interference and that all the symbols that are in a dwell interval that is hit but not detected will be in error. Also, they have analyzed the scheme for $\gamma=0$ and $\gamma=1$ only. The situation for $\gamma=1$, is more difficult to analyze in our model.

1.3 Simplification and comparisons for partial-band jamming only

In comparing the performance of the different side information schemes, we did not include multiple-access interference. Instead, our initial focus is on partial-band jamming and wide band noise as the only source of interference. Multiple-access interference was not included for three reasons. The probability that a packet can be decoded involves eleven nested summations and is very time consuming to calculate. This makes a detailed comparison study all but impossible. Also, solving for the erasure and error probabilities for multiple-access interference involves some simplifying assumptions that are not necessary for partial-band interference. Finally, we found that network performance was much more sensitive to the partial-band interference model than to the multiple-access interference model.

The expression for the probability that a packet can be decoded correctly can be simplified considerably when multiple-access interference is not included. In effect, P_h is set to zero and the erasure and error probabilities that are conditioned on multiple-access interference are not needed. For the remainder of this section, the conditional probability of erasure given that partial-band interference is present is denoted by β, and the conditional probability of error given partial-band interference is present is denoted by p_J.

For dwell interval side information, there are $2N_{ts}$ test symbols included in each dwell interval, and the test symbols are from a known sequence. The receiver examines the received test symbols in a particular dwell interval, and if more than γ test symbols are in error, the dwell interval is erased. In a dwell interval that is hit by partial-band interference, it is assumed that the partial-band interference is present during all of the dwell interval. The partial-band interference occupies a fraction ρ of the band, and the two-sided power spectral density in this region of the band is $\rho^{-1}N_I/2 = N_J/2$. The wide-band noise has power spectral density $N_0/2$.

The probability of correctly detecting partial-band interference when it is present is just the probability that more than γ test symbols are in error. This probability is given by

$$\begin{aligned}\beta &= 1 - \sum_{j=0}^{\gamma} \binom{2N_{ts}}{j} p'^j (1-p')^{2N_{ts}-j} \\ &= 1 - F(\gamma; 2N_{ts}, p'),\end{aligned}$$

where p' is the error probability for a binary test symbol transmitted in a dwell interval that is jammed and is given by

$$p' = \frac{1}{2}\exp\left(-E/2(N_0 + N_J)\right). \tag{3}$$

The received energy per binary symbol is E.

Similarly, the probability of falsely detecting partial-band interference when it is not present is given by $\alpha = 1 - F(\gamma; 2N_{ts}, p)$, where p is the error probability for a binary test symbol transmitted in a dwell interval that is not jammed and is given by

$$p = \frac{1}{2}\exp(-E/2N_0). \tag{4}$$

Next, the error probability for a code symbol when partial-band interference is present is $p_J = 1-(1-p')^m$. Note that $m = \log_2 n$ is the number of binary symbols per code symbol. The error probability for a code symbol when partial-band interference is not present is $p_0 = 1-(1-p)^m$.

We have examined the ratio threshold test (RTT) which is a symbol side information scheme. From the symbol error and erasure probabilities for the RTT given in [1], α, β, p_J, and p_o can be calculated easily. From [1], $p_t(\sigma^2)$ is the probability of symbol error and $p_e(\sigma^2)$ is the probability of symbol erasure when the noise has spectral density σ^2. When partial-band interference is present $\sigma_I^2 = \rho^{-1}N_I/2 + N_0/2$, and when only noise is present $\sigma_N^2 = N_0/2$. Then $\alpha = p_e(\sigma_N^2)$, $\beta = p_e(\sigma_I^2)$, the probability that a symbol is in error given that it has not been erased and that partial-band interference is not present is

$$p_0 = \frac{p_t(\sigma_N^2)}{1 - p_e(\sigma_N^2)},$$

and when partial-band interference is present the symbol error probability given that it has not been erased is

$$p_J = \frac{p_t(\sigma_I^2)}{1 - p_e(\sigma_I^2)}.$$

A third scheme for the generation of side information is given in [6] and uses parity binary symbols as the test symbols. The analysis given in [6] assumes that multiple-access interference is the primary type of interference. Slight modifications are made here to account for partial-band instead of multiple-access interference.

Consider the parity side information scheme when $\gamma=0$. The previously developed equations for the packet error probability for dwell interval side information can be used, so all that needs to be done is to calculate α, β, p_J, p_0. There are L codewords per dwell interval, and each codeword has a parity test symbol. The probability that a dwell interval is erased is

$$\beta = 1 - (1 - \beta')^L,$$

where β' is the probability that any one of the L code symbols is erased. A code symbol is erased if an odd number of binary symbols are in error (including the parity symbol). So,

$$\beta' = \sum_{\text{odd } c} \binom{m+1}{c} p'^c (1 - p')^{m+1-c}.$$

The formulas for α are the same except that no partial-band interference is present. So,

$$\alpha = 1-(1-\alpha')^L \text{ , and}$$

$$\alpha' = \sum_{\text{odd } c} \binom{m+1}{c} p^c (1-p)^{m+1-c} .$$

The probability that a code symbol is correct given that it has not been erased is the conditional probability that none of the binary symbols (including the parity symbol) are in error given that the symbol has not been erased. So, when partial-band interference is present, the probability that a code symbol is in error given that it has not been erased is

$$p_J = 1 - \frac{(1-p')^{m+1}}{1-\beta'} ,$$

and when partial-band interference is not present, it is

$$p_0 = 1 - \frac{(1-p)^{m+1}}{1-\alpha'} .$$

When $\gamma = L$, symbols are erased on a symbol-by-symbol basis instead of erasing the entire dwell interval. So, p_J, p_0 are not changed and α is taken to be α' and β is taken to be β'.

To be able to compare the side information schemes, certain precautions must be made to ensure that the comparison is fair. A packet consists of L codewords with each codeword consisting of n symbols from a (n,k) Reed-Solomon code. The codewords are fully interleaved, so a packet consists of n dwell intervals and each dwell interval contains L code symbols plus any binary test symbols. One possible set of requirements for a fair comparison is that the rates for the two schemes be the same. Also, the number of dwell intervals per packet should be the same; this implies that n is the same for both schemes. Finally, the number of binary symbols per dwell interval should be the same; this implies that $L_s m = L_{ts} m + 2N_{ts}$ where L_s and L_{ts} are the number of codewords per packet for the symbol and dwell interval side information schemes, respectively and $m = \log_2 n$. For the symbol side information scheme the rate is $r = k/n$, while for the dwell interval side information scheme the rate is

$$r' = \frac{k'}{n}\frac{mL_{ts}}{(mL_{ts} + 2N_{ts})}.$$

The parity test symbol scheme has the same constraints as the test symbol scheme with the additional condition that the number of test symbols in a dwell interval equal the number of code symbols in the dwell interval (i.e., $L_{pts} = 2N_{pts}$).

A computer program has been written to calculate the packet error probability for the test symbol, ratio threshold, and parity test symbol tests. The received energy per binary symbol, E, is related to the energy per information symbol, E_b, by $E = rE_b$, where r is the rate of the coding scheme. For the test symbol and ratio threshold tests, the program finds the optimal γ and θ at each E_b/N_I. For the parity test symbol test, the packet error probability is calculated for $\gamma=0$ and $\gamma=L$.

Examining the test symbol scheme first, a (32,12) Reed-Solomon code is used with 30 codewords per packet. The performance of the test symbol scheme versus E_b/N_I for various values of the number of test symbols is illustrated in Figure 1. Using no test symbols is the same as errors-only decoding. Figure 2 is similar but only shows the results when the number of test symbols is 0, 10, 20, and 30. When the partial-band interference is very strong, the test symbol scheme works well, but as the interference becomes weaker the performance becomes worse than in the errors-only case. When E_b/N_I is large, the best γ becomes large and very few dwell intervals are erased. In effect only errors-only decoding is used, so the tests with a larger number of test symbols perform worse since they have a smaller rate (i.e., the received energy per code symbol is smaller).

Next, we compare the test symbol scheme with the other side information schemes. For a fair comparison the rates and the number of binary symbols per dwell interval must be the same for all schemes. For the test symbol scheme (and the parity test symbol scheme), a (32,12) Reed-Solomon code is used with 30 codewords per packet and 30 test symbols. For the ratio threshold test (and errors only decoding), a (32,10) code is used with 36 codewords per packet. All three schemes have rate 0.3125, 180 bits per dwell interval, and 32 dwell intervals per packet.

The performance of all the side information schemes considered here with $E_b/N_0 = 14.3$ dB and ρ=0.2 is shown in Figure 3. The ratio threshold test performs better than errors-only decoding for all E_b/N_I. The test symbol scheme performs better than the ratio threshold test when E_b/N_I is small because is has a higher probability of detecting interference when it is present and a smaller false alarm probability. But, the test symbol scheme performs worse than even errors-only decoding when E_b/N_I is large since there are few erasures and the code has less redundancy than the schemes without extra test symbols. The dwell parity test (when γ=0) performs very poorly because the probability that a dwell interval is erased when no interference is present is very large for this test. The symbol parity test (when γ=30) performs very good when E_b/N_I is large since there are few errors and the parity test can detect an odd number of errors, but performs poorly otherwise since there may be an even or odd number of errors.

Figure 4 is similar to Figure 3, except that E_b/N_0=16.0 dB for Figure 4. The major difference is that the dwell parity scheme performs much better since the false alarm probability is much smaller. That is, in a dwell interval that is not jammed, the lower noise level results in fewer errors so that the dwell interval is less likely to be erased. This suggests that if the optimal γ is used, the parity test scheme may perform very well.

The performance when ρ=0.4 is shown in Figure 5. The same observations as above apply, but the improvement from the various side information schemes over errors-only decoding is less. We have examined other combinations of coding rates and interference levels and have observed similar results.

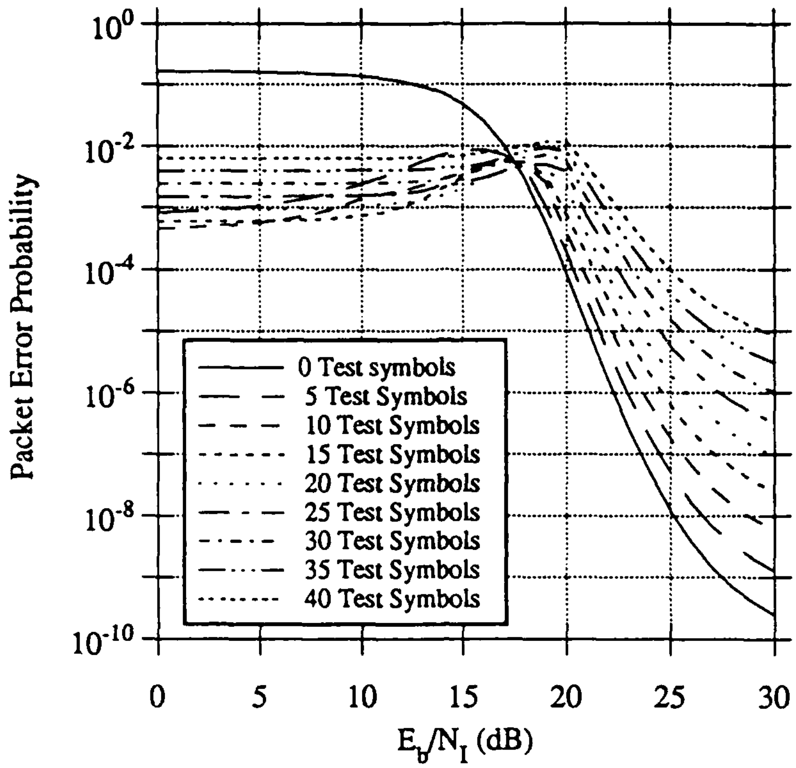

Figure 1. Performance of the test symbol scheme.

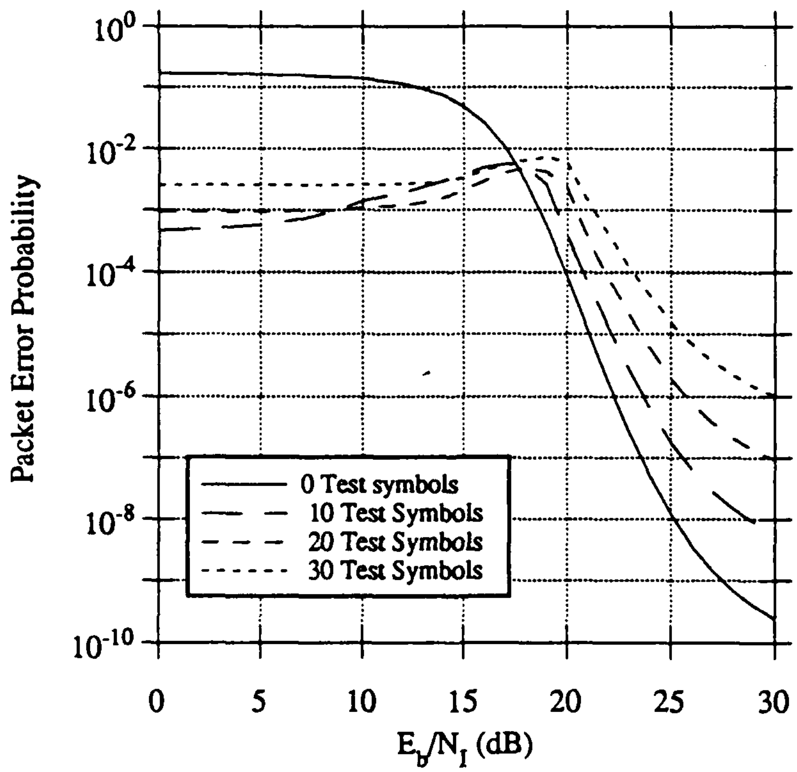

Figure 2. Performance of the test symbol scheme for the values of N_{ts} of greatest interest.

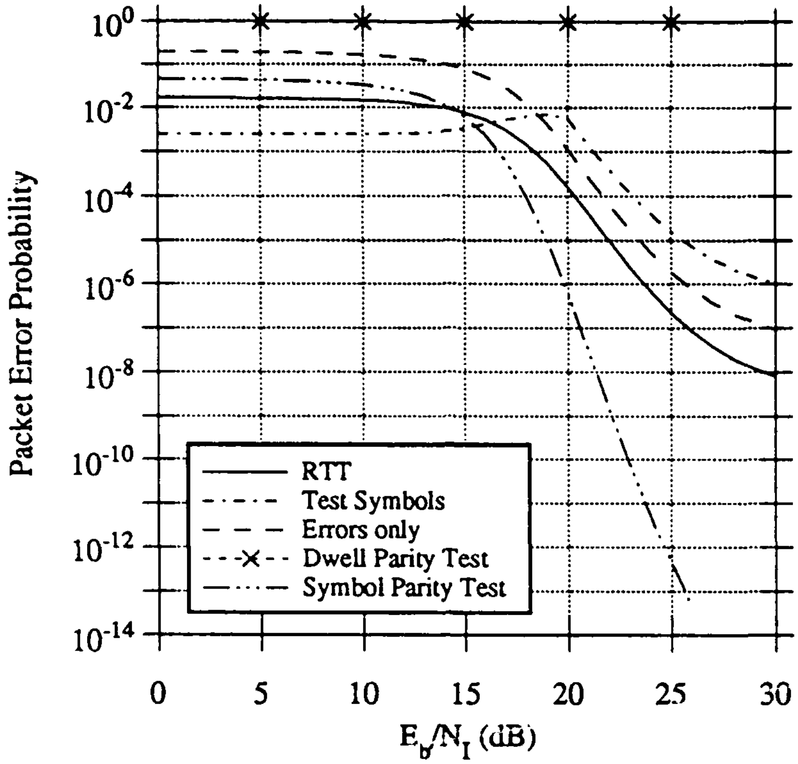

Figure 3. Performance of the side information schemes (E_b/N_0 = 14.3 dB, ρ=0.2).

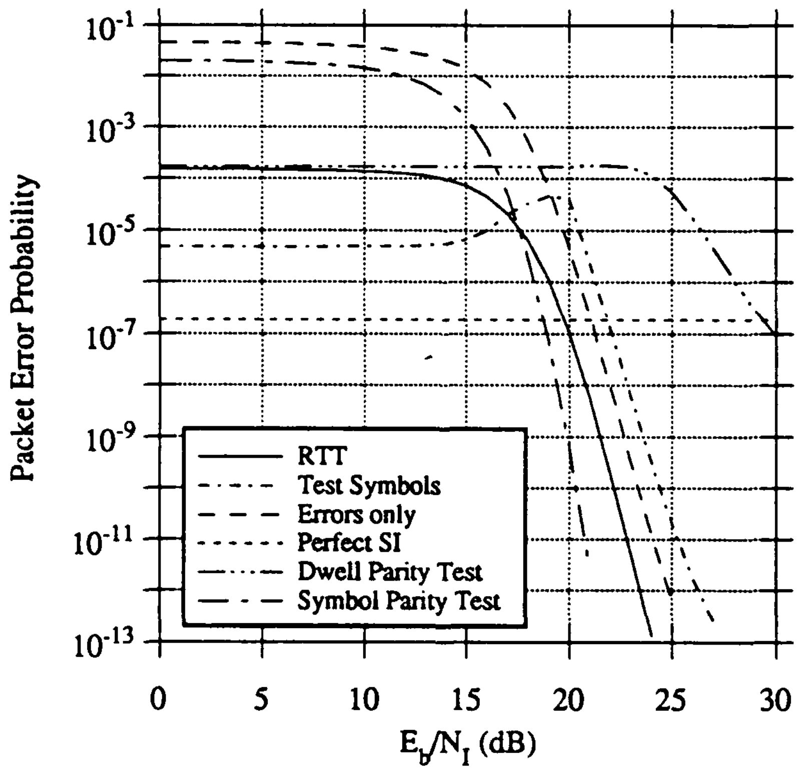

Figure 4. Performance of the side information schemes (E_b/N_0 = 16.0 dB, ρ=0.2).

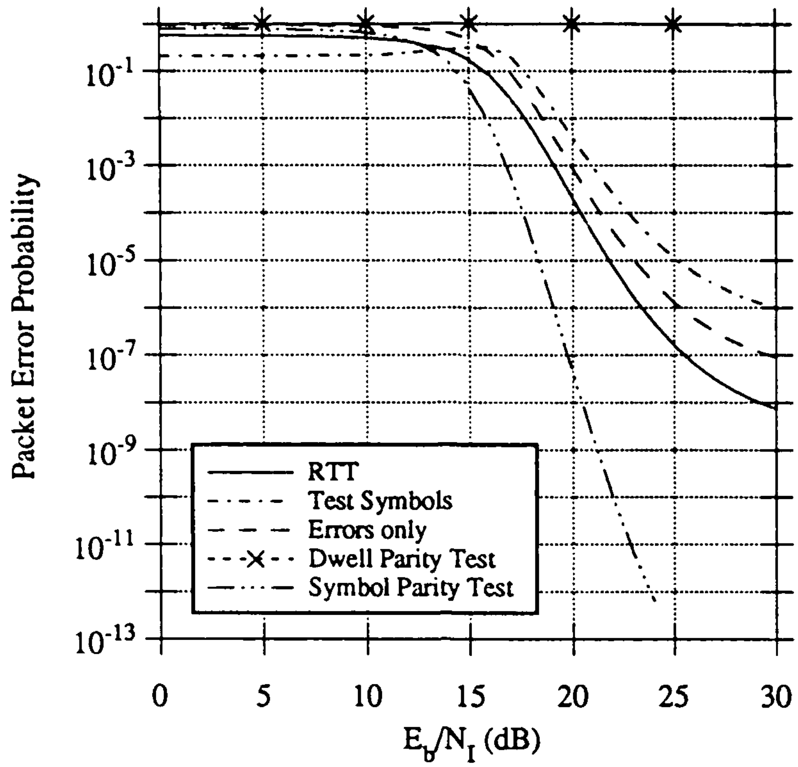

Figure 5. Performance of the side information schemes (E_b/N_0 = 14.3 dB, ρ=0.4).

1.4 Error and erasure probabilities for multiple-access and jamming

The calculation of the conditional probabilities of error and erasure for the side information scheme that uses test symbols is developed in this section. It is an extension of [9]. There are $2N_{ts}$ binary test symbols included in each dwell interval, and the test symbols are from a known sequence. Half the test symbols are located at each end of the dwell interval, and if more than γ test symbols in either of the two groups are in error, the dwell interval is erased. Three types of interference are included in the model: multiple-access (MA), partial-band, and wide-band Gaussian interference. In a dwell interval that is hit by partial-band interference, it is assumed that the interference is present during the entire dwell interval. A dwell interval is subjected to wide-band interference, and it may be subjected to partial-band or multiple-access interference or both. The conditional probability that a dwell interval is erased and the conditional probability a code symbol is in error can be calculated for the four types of

interference environments. Table 3 lists the types of interference and the erasure and error probabilities.

Table 3. Conditional erasure and error probabilities.

Type of interference	Probability of erasure	Probability of error
both	β_3	p_3
MA	β_2	p_2
jamming	β_1	p_1
quiescent	α	p_0

First, assume that only quiescent noise is present. The probability that a particular sequence has more than γ binary test symbols in error is $\alpha' = 1 - F(\gamma; N_{ts}, p)$, where p is the probability that a binary symbol is received in error and is given in (4). A dwell interval is erased if either one of the two test sequences has more than γ binary test symbols in error, so the conditional probability that a dwell interval is erased given that quiescent noise is present only is $\alpha = 1 - (1 - \alpha')^2$. The probability that a code symbol is received in error given that only quiescent noise is present is $p_0 = 1 - (1 - p)^m$.

Next, assume that partial-band jamming is present in the dwell interval. The probability that a particular sequence has more than γ binary test symbols in error is $\beta_1' = 1 - F(\gamma; N_{ts}, p')$ where the probability that a binary symbol is received in error given that partial-band interference is present is given in (3). The conditional probability that a dwell interval is erased given that partial-band interference is present is $\beta_1 = 1 - (1 - \beta_1')^2$. And, the probability that a code symbol is received in error given that partial-band interference is present is $p_1 = 1 - (1 - p')^m$.

We use the same assumptions as given in [10] for the calculations when only multiple-access interference is present. Namely, only one of the two sequences is hit by multiple-access interference, and the binary test symbols are in error with probability 1/2. The probability that a particular sequence has more than γ binary test symbols in error is $\beta_2' = 1 - F(\gamma; N_{ts}, 1/2)$, and the conditional probability that a dwell interval is erased given that multiple-access interference is

present is $\beta_2 = 1-(1-\beta_2')(1-\alpha')$. Also, as in [10], we assume that a symbol that is hit by multiple-access interference but is not erased is in error, so p_2=1.

Finally, when both partial-band and multiple-access interference are present, we assume that one of the test sequences is hit by both multiple-access and partial-band interference and that the symbols in this sequence are in error with probability 1/2. It is assumed that the other test sequence is hit by partial-band interference only. So, the conditional probability that a dwell interval is erased given that both partial-band and multiple-access interference are present is $\beta_3 = 1-(1-\beta_2')(1-\beta_1')$. As before, all symbols in a dwell interval that is hit by multiple-access interference are in error, so p_3=1.

1.5 Simulation of errors and erasures

The test symbol side information scheme has been implemented in our simulation program . The receiver must attempt to decode the packet in the presence of a fixed number of frequency-hop transmissions that are not on the same hopping pattern. There may also be partial-band interference. The simulation program determines the number of dwell intervals that are hit by multiple-access interference, partial-band interference, both, and none. Next, the number of dwell intervals that are erased for each of the four types of interference environments is simulated using the conditional erasure probabilities. If more then $n-k$ dwell intervals are erased, none of the codewords in the packet can be decoded and the number of erasures is reported to the receiver. Otherwise, for each codeword the number of code symbol errors is simulated using the conditional error probabilities. If the number of symbol erasures and twice the number of symbol errors in the received word is greater than $n-k$, the codeword cannot be decoded. In this situation, the number of symbol errors is not known by the receiver, and our convention is that the receiver should assume the number of symbol errors is such that the number of erasures plus twice the number of errors is just greater than $n-k$. If the codeword can be decoded, the receiver knows the number of symbols that are in error in the received word.

The average number of symbol errors for the received words in the packet is determined, and this along with the number of erasures is used in the forwarding and routing protocols.

2. USE OF SIDE INFORMATION IN PACKET RADIO NETWORK PROTOCOLS

We have examined two different types of protocols for FH packet radio networks that can incorporate side information. *Forwarding protocols* provide rules for forwarding a packet to the next radio on a route to the packet's destination. A radio will often have two different routes to the destination, and this allows the forwarding protocol to change routes based on the current *local* conditions without waiting for a routing update. As a result, the forwarding protocol can react quickly to changes in the local interference conditions. *Routing protocols* are concerned with establishing routes between every pair of radios. The routing protocol typically takes more time than the forwarding protocol to react to changes in the network, but the eventual response of the routing protocol can account for *global* changes as well as local changes in the interference environment and other network conditions. Hence, the routing protocol seeks a long-term global solution to a problem in the network, whereas the forwarding protocol seeks a short-term local solution.

In this section we define some new forwarding and routing protocols that use side information, and we describe some other typical forwarding and routing protocols. The radios in the network use time-slotted, receiver-directed FH spread-spectrum signaling. This type of signaling imposes special constraints on the protocol design; for example, active acknowledgements are required and data packets can be received by the intended destination only. One of the key observations from this study is that reliable side information can be obtained from the demodulator and decoder in the FH receiver, and it can be used effectively in the network protocols to increase the throughput and decrease the delay.

2.1 Forwarding protocols

In our investigation of forwarding protocols, we are concerned with the effectiveness of the forwarding procedure as a short-term method for routing around localized jamming in a FH packet radio network. Forwarding protocols allow for local routing changes in the time periods between routing updates in a network with dynamic routing. The short-term changes permitted by the forwarding protocols affect routes near the jammer only.

To examine the effectiveness of the forwarding protocols, the routing tables are held fixed. Fixing the routing tables and examining the forwarding protocols allows a more detailed examination of the impact of the use of side information in permitting the radios to adjust quickly to changes in the interference environment. In particular, we can determine how quickly a neighborhood of radios can react to the movement of a jammer.

Each radio has stored in its routing table two routes to each destination in the network except the neighbor radios (there is only one route to a radio that is one hop away). We are concerned with the two outgoing links associated with these two routes. The designations for these links are different for different forwarding protocols.

2.1.1 Forwarding based on errors and erasures

The side information used in this forwarding procedure is based on the count of errors and erasures that can be obtained from the decoder of a successfully acquired packet. For each packet that a radio acquires, the decoder provides the number of erasures and errors that occur in that packet (see Section 1.5). The errors and erasures metric for a packet, referred to as the *EE metric*, is defined to be the number of erasures plus twice the number of errors in that packet. This value is then designated as the resistance for the radio that received the packet, and the radio includes its resistance in the header of all packet transmissions. When a neighboring radio has received a packet, it learns the current resistance value for the radio that transmitted this packet, and it stores the new value as the resistance for the link to the transmitting radio. The forwarding protocol based on the EE metric is referred to as the *EE-based forwarding protocol.*

If a radio has a packet to transmit in a given packet interval, it examines the two outgoing links in its table that correspond to the packet's destination. The link with the smaller resistance value is selected as the *preferred outgoing link* for that packet interval. The link on which the radio chooses to transmit the packet will be referred to as the *designated link* for that packet in that packet interval.

The way in which the designated link is selected in the EE-based forwarding protocol is as follows. If the transmission attempt is one of the first three, the designated link is the preferred link. In the fourth transmission attempt, the designated link is the outgoing link in the table that was not used in the third attempt (recall, there are only two outgoing links in the table). The fifth and sixth attempts are made on the same link as the fourth. Of course, not all of these attempts are needed for each packet; if any transmission attempt is successful, the radio selects the next packet and begins a new transmission cycle. On the other hand, if none of the six attempts is successful, the packet is discarded.

In all of the above, an exception is made when there is only one route to the packet's destination. For example, there is only one route to a neighbor radio, and that route consists of a single link; in the case the same link is used for all six attempts.

2.1.2 Forwarding based on errors, erasures, and acknowledgements

A modified version of the errors and erasures metric takes acknowledgements into account. It is referred to as the *EEA metric*, and the corresponding forwarding protocol is called the *EEA-based forwarding protocol*. A radio increments the resistance value by one for a neighbor radio each time the radio makes a transmission to that neighbor and does not receive an acknowledgement. The modification deals only with what happens when no acknowledgement is received, and it has the effect of increasing the resistance by an amount proportional to the number of consecutive acknowledgements that have not been received since the last time a new resistance value was obtained.

Because the resistance values are being updated more often in the EEA-based protocol than in the EE-based protocol, a packet is forwarded on the primary link for the first five attempts, rather than the first three attempts as in the EE-based protocol. If a sixth forwarding attempt is needed it is made on the link not used for the fifth attempt.

2.1.3 The primary 6/3 forwarding protocol

The primary 6/3 protocol is defined in [12, 14]. Basically, the routing algorithm designates one of the two outgoing links for a given destination as the primary link, and the other is the secondary link. The first three attempts to forward a packet take place on the primary link. If after the third attempt the packet has not been acknowledged, the next attempt is made on the secondary link, and this link is used for the remaining attempts to forward the packet. Note that no metric is defined for this protocol, and the primary and secondary links are fixed.

2.1.4 The good-link 6/3 forwarding protocol

The protocol known as good-link 6/3, also defined in [12,14], combines stored information about the link which was last used successfully with the current feedback from the acknowledgement packets. The primary and secondary links are the same as in the primary 6/3 protocol. A packet is initially forwarded on the link that was used for the previous packet with the same destination, provided that previous packet was transmitted successfully, and this link is employed for the first three transmissions, if that many are required. If all three are unsuccessful, the radio switches to the alternative link for the remaining transmission attempts (e.g., if it first used the secondary link, it switches to the primary). If the previous packet with the same destination was not successful on its last forwarding attempt, the radio switches to the other link if there is one. Note that there is not another link if the packet is being transmitted on the final link in the route (i.e., the link to the destination). The primary and good-link protocols have been investigated in more detail in [12,14]

2.2 Errors and erasures in the routing protocols

Least-resistance routing (LRR) is an adaptive, decentralized routing algorithm that accounts for multiple-access interference, jamming, and other partial-band interference at each of the radios in the network. Each radio maintains a measure of its own reception quality for packets coming from each of its neighbors, and it can pass this information along to other radios by means of a number of different mechanisms, including packet radio organization packets (PROP's) and data

packets. The metric for least-resistance routing reflects the channel conditions as seen by a frequency-hop receiver. A more detailed discussion of the basic principles of LRR is given in [11, 13, 15].

The EE metric discussed in Section 2.1.1 has also been examined for use in LRR. When a radio has acquired a packet, a new resistance is calculated from the information supplied by the decoder on the number of errors and erasures for the packet. The resistance for a route is just the sum of the resistances for each link.

We have also examined the EEA metric in LRR. Each radio calculates its own resistance as before, and the resistance values are propagated throughout the network. However, for the EEA metric, when a radio makes a transmission to a neighbor radio and does not receive an acknowledgement, the radio increments the resistance it has stored for that neighbor radio. The resistance for each route through the neighbor radio is then updated to reflect the new resistance value on the link to the neighbor radio.

Previous investigations of LRR have used a metric that assumes that a radio has perfect knowledge of its interference environment. During each packet interval that a radio is not transmitting, it determines the number of frequency slots that are hit by partial-band or multiple-access interference. From this the radio can calculate the probability that it can acquire and decode a packet. The negative logarithm of this probability is used as the resistance for the radio. This is called the LP (log-probability) metric [11,13,15]. Note that the perfect side information is used for determining the resistance value only. The side information available from the test symbols (rather than perfect side information) is all that is assumed to be available for decoding the packet.

Another metric examined in LRR assigns resistance one to each link in the network. With this metric the route with the least resistance is also the route with the fewest number of hops to the destination. The modification to the errors and erasures metric is also used here. When a radio makes a transmission to a neighbor radio and does not receive an acknowledgement from that neighbor it increments the resistance it has stored for that neighbor radio. This is called the CA (constant with acknowledgements) metric.

In our previous Phase I contract [11], we implemented a modified version of tier routing [4,5]. Each radio determines certain statistics regarding successes and failures of packet transmissions to and from its neighbors. Based on these statistics, each neighbor is flagged as good or bad. To be a good neighbor a certain fraction of the recent transmission attempts must have been successful. Packets are forwarded on the shortest length route to the destination that uses good links only.

A simple forwarding protocol is used with the routing protocols examined here. When a packet is to be forwarded, the radio uses the link for the route with the lowest resistance for the first three transmissions attempts. If after the third attempt the packet has not been acknowledged, the next attempt is made on the link for the alternative route (i.e., the route not used for the third attempt) and this link is used for the remaining attempts to forward the packet. Once exception occurs if the route designated for the final three forwarding attempts is removed from the routing table, in which case, the route with the lowest resistance is used for the remaining attempts. The number of transmission attempts on the link for the route with the lowest resistance is increased to five for some of the investigations of the EEA metric.

2.3 Subnetwork topology and interference model

Results of a computer simulation of a time-slotted FH packet radio network permit comparison of the forwarding protocols and of LRR with different metrics and tier routing. In the simulation, FH radios are grouped into three categories: FH packet radios that are interacting closely in a local network that we refer to as a *subnetwork*, FH packet radios that are not part of the subnetwork (although they may be able to reach the subnetwork via gateways), and other FH radios. All of these radios contribute interference in the subnetwork, but only the radios within the subnetwork interact in the forwarding and routing protocols. This basic model for the interference environment has been used in previous work [11,12,13,14,15] so only the key features and changes are reported here.

The model for the FH packet radio network employed in the simulation is illustrated in Figure 1. The *subnetwork* consists of the radios numbered 1–12. We envision that the subnetwork is located in the interior of the overall network, and that a significant amount of traffic will flow through the subnetwork, entering via radios 5–8. The traffic generated at radios 5–8 in the simulation is intended to represent traffic originating at these radios together with traffic that is routed through these radios from the packet radios that are not part of the subnetwork. As a result, the packet generation rates for radios 5–8 are twice those for the other radios in the subnetwork. This is the only way in which traffic from outside the subnetwork is considered in the simulation, so traffic generation by radios not in the subnetwork need not be simulated. However, the interference due to transmissions by the radios outside the subnetwork is accounted for in the simulation. This requires a simulation of the number of FH transmissions heard by each radio in the subnetwork.

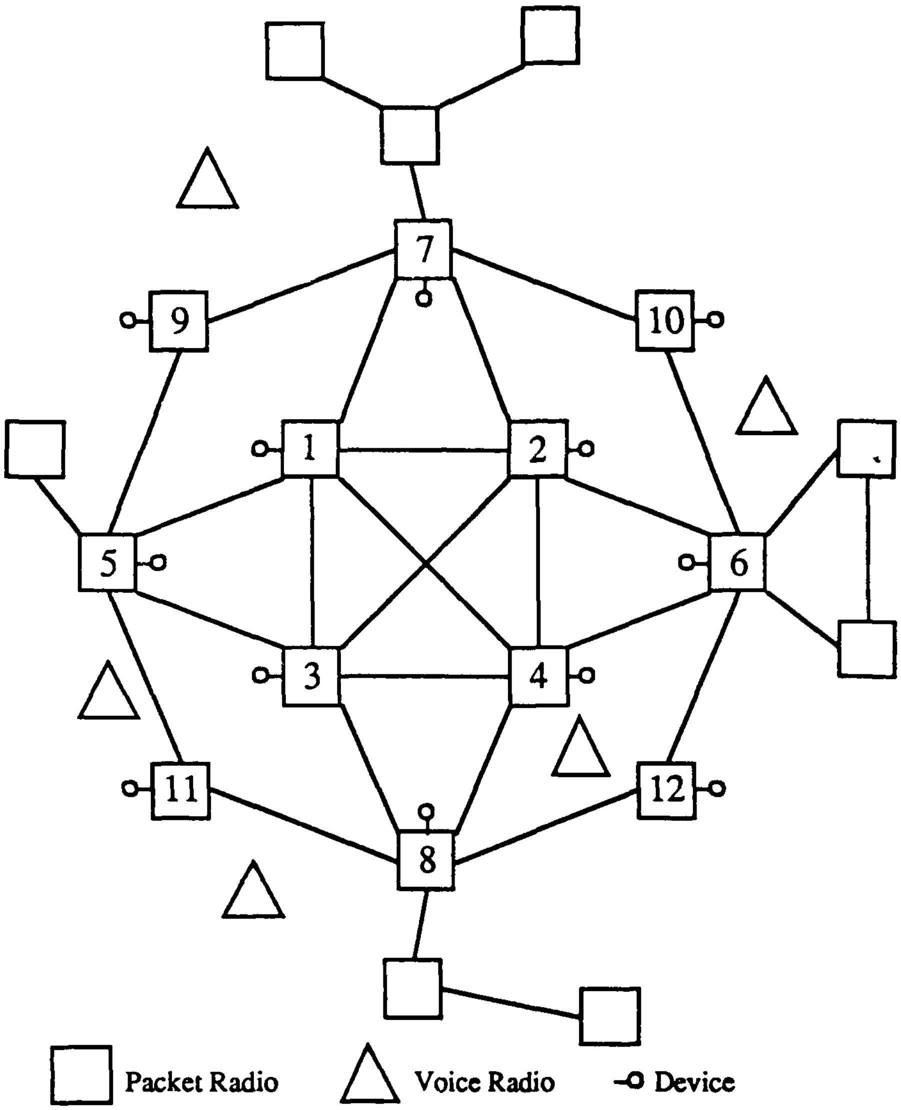

Figure 1. Model for the packet radio network topology.

In order to keep track of the number of FH transmissions from outside the subnetwork, the subnetwork is divided into nine regions. Eight local regions are shown in Figure 2; a global region, which is not shown, includes all radios in the subnetwork. There is a discrete-time Markov chain for each region. The state of the chain for a given region specifies the number of interfering transmissions from outside the subnetwork that are heard by radios in that region. The Markov chain for each region is the same, and it is shown in Figure 3. In the figure for the Markov chain, only the transition probabilities to different states are shown. The probability of

staying in the current state in the next packet interval is, of course, such that all of the transition probabilities for a state sum to 1. Each Markov chain is independent of all others.

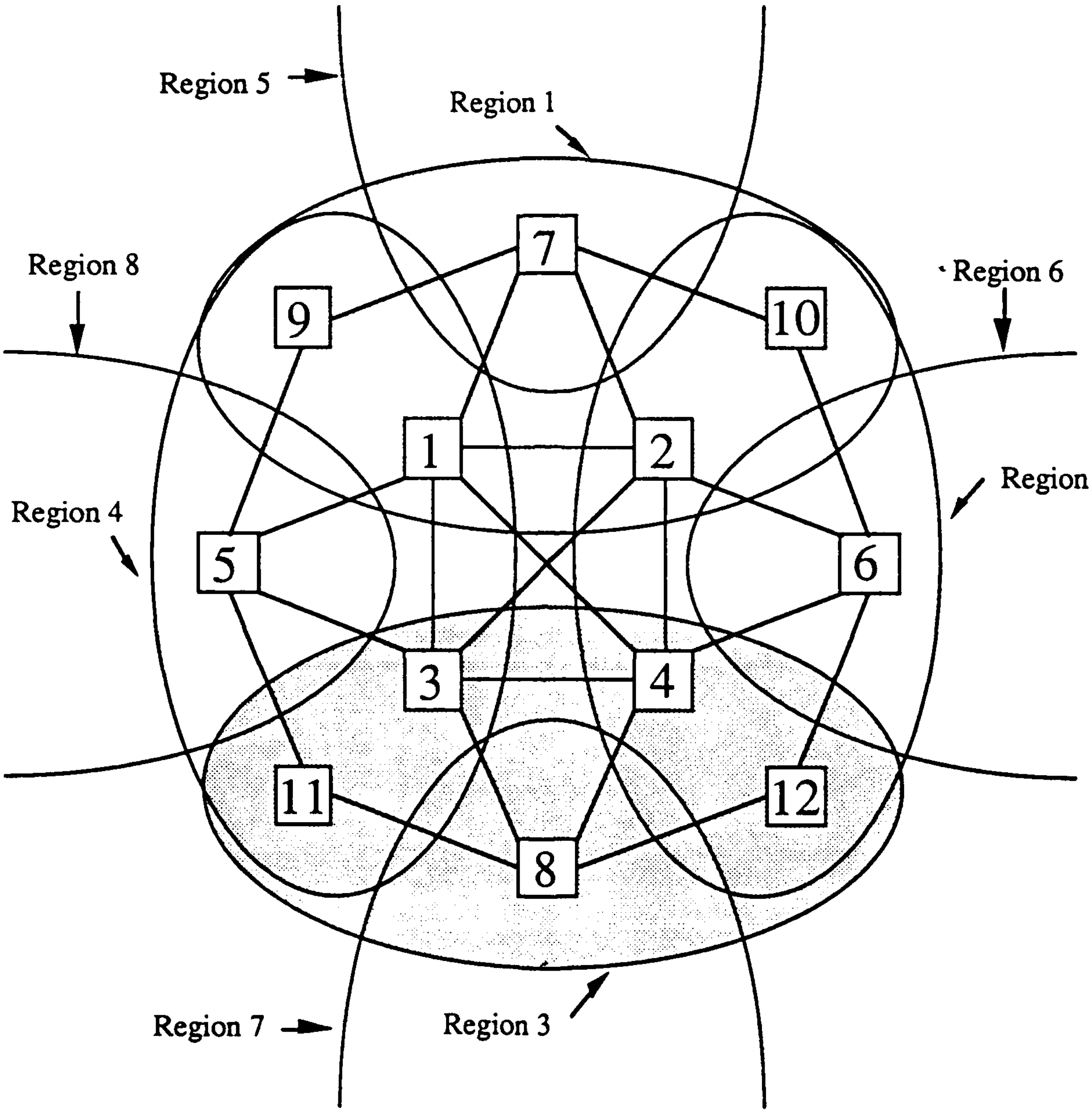

Figure 2. Interference regions for the subnetwork.

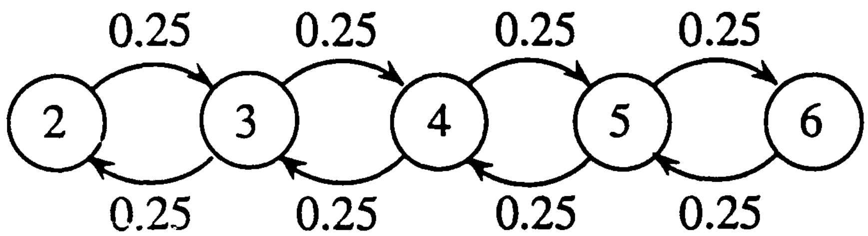

Figure 3. Markov chain for all regions.

Another significant improvement to the simulation during the Phase I investigation is the jammer model. The simulation has been enhanced to include two partial-band jammers. This makes the forwarding and routing considerably more complex, since many more of the potential routes are jammed. One of the jammers is initially located at radio 1 and the other is located at radio 4. A jammer affects only the radio it is located near. The *period* is the number of packet time intervals that the jammers are located near a particular radio. After the period has expired the jammer near radio 1 moves near radio 3 and the jammer near radio 4 moves near radio 2. When the next period expires the jammers move back to their original positions. The fraction of the band with interference is denoted by ρ.

The descriptions for the underling protocols for the packet radios are the same as used in [11,12,13,14,15], so they will not be repeated here. These protocols are concerned with basic issues such as the retransmission policy and flow control. They are not directly involved in any of the forwarding or routing protocols, and they behave identically for all of the protocols tested here. One such issue is the model for receiving a packet transmission. A packet may not be received for a variety of reasons, such as the receiver being busy (i.e., the radio is transmitting or another packet has been acquired). Even if the receiver is not busy, the packet will not be received if there is interference in both of the two synchronization dwell intervals. And, even if synchronism is acquired, the packet will not be received if the radio cannot decode the packet. During each packet time interval, the interference environment is fixed, and from this the number of errors and erasures is simulated to determine if the packet can be decoded, as discussed in Section 1.5.

The protocols for flow control have not been completely implemented during the Phase I investigation. The network throughput increases nearly linearly with the offered traffic rate for

small to moderate levels of offered traffic, but then the network throughput actually decreases substantially when the offered traffic rate is increased beyond a certain level. The basic reason is that, when the network is congested, many packets do not reach their destinations, but nevertheless they use network resources during the time they are in the network. Future work will examine flow and congestion control procedures, and we expect that these protocols can be easily incorporated into LRR.

2.4 Simulation results

The (32,16) extended Reed-Solomon code is used and there are 100 frequency slots. There are 30 codewords per packet and 10 test symbols per dwell interval. The test symbols are divided into two groups, and if any of the test symbols are in error, the dwell interval is erased (i.e., $\gamma=0$). The ratio of the signal power to jammer noise power is 0 dB. By analyzing the probability that a packet can be received, it was found that setting $\gamma=0$ gives the largest such probabilities for all combinations of multiple-access and partial-band interference used in this study.

The throughput, delay, and end-to-end success probability are examined for four designated origin-destination pairs. These pairs are (5,6), (6,5), (7,8), and (8,7), and all packets generated at radios 5–8 are for the corresponding destinations only. These packets are *marked* and their flow through the subnetwork is monitored to determine the throughput, delay, and probability of success. This traffic represents a combination of packets generated by attached devices and packets that arrive at the radio from outside the subnetwork. Traffic is generated at radios 5–8 independently from packet interval to packet interval. The probability a packet is generated in a given packet interval is p. Traffic is generated at the remaining radios in the same manner, but the generation probability is $p/2$. The destinations for these packets are randomly selected with a uniform distribution over all other radios in the subnetwork. The packets generated at these radios are forwarded to their destinations, but they do not contribute to the measured throughput, delay, or probability of success.

Three statistics are collected by the simulation: *end-to-end throughput*, the average number of marked packets that reach their destinations per packet interval; *end-to-end probability of success*, the average fraction of marked packets that reach their destinations; and *end-to-end delay*, among those marked packets that reach their destinations, the average number of packet intervals required to do so.

Because packets that are discarded do not contribute to the delay statistic, this statistic is meaningful only if the end-to-end probability of success is high for the simulation run. Packets discarded before reaching their destinations must be detected by the end-to-end acknowledgement protocol, which is not included in this simulation, and rescheduled for transmission at a later time. The rescheduling delay will typically dominate other components of the end-to-end delay if the end-to-end probability of success is low.

2.4.1 Results for forwarding protocols

Figure 4 shows certain of the primary and secondary outgoing links for radios 5–8 when there is more than one shortest path to a destination. For example, when radio 5 has a packet for radio 2, 4, or 6, the primary link is to radio 1 and the secondary link is to radio 3. When radio 5 has a packet for radio 7 or 10, the primary link is to radio 9 and the secondary link is to radio 1. And when radio 5 has a packet for radio 8 or 12, the primary link is to radio 3 and the secondary link is to radio 11. Analogous assignments are used for all the other radios, except as noted below. When there are two shortest length routes to a destination, the primary link is for the route that starts on the left side of the network (from the source's point of view), while the secondary link is for the route that starts on the right side. An exception is made when radio 1 is forwarding to radios 6 or 8. The primary outgoing link is $(1, 2)$ for radio 1 when it is forwarding a packet whose destination is radio 6; the secondary outgoing link is $(1, 4)$. When radio 1 forwards a packet whose destination is radio 8, link $(1, 3)$ is the primary link, and link $(1, 4)$ is the secondary. Radios 2, 3, and 4 use analogous assignments: the secondary link is always taken to be the "diagonal" link. There are more than two outgoing links on the shortest routes from radio 1 to

radio 12. Here link (1,2) is the primary and (1,3) is the secondary. When radio 1 has a packet for radio 10 or 11 there is no secondary link; the primary link is to the neighbor on the unique shortest length route and is used for all transmission attempts. Similarly, only a primary link is defined when forwarding a packet to a neighbor radio. When radio 9 has a packet for radio 2, 3, 6, or 8 the primary link is to the neighbor on the shortest length route and the secondary link is to radio 9's other neighbor; in this situation the route along the secondary link is one hop longer. As before, these rules are extended to the other radios in the subnetwork.

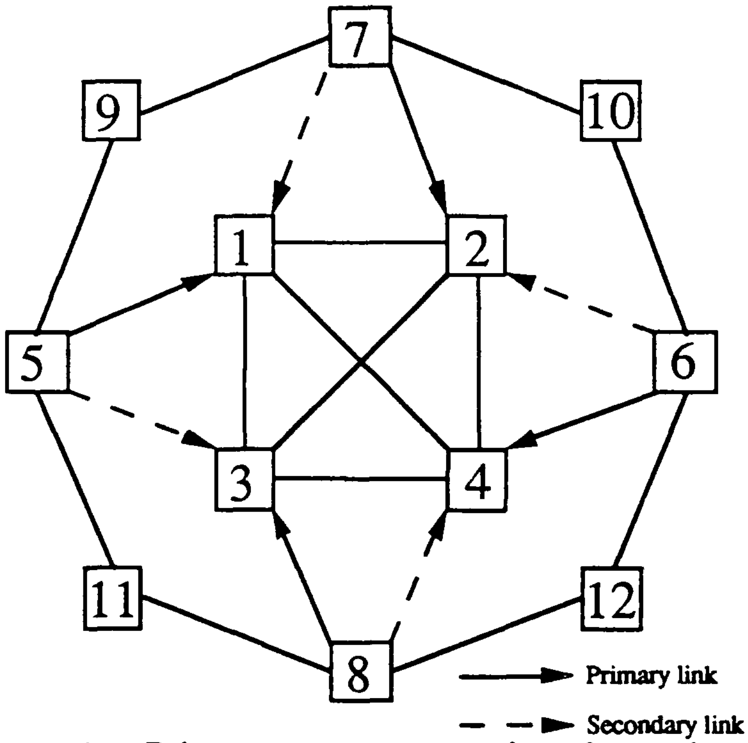

Figure 4. Primary and secondary links for radios 5-8.

For the investigation of the forwarding protocols reported here, the jammer period is 100 packet time intervals and 40% of the band contains partial-band interference. The first set of simulations use a signal-to-noise ratio of 13.0 dB which corresponds to a bit error rate of 4.7×10^{-3}. The results for the four forwarding protocols are shown in Figures 5–7. Examining the throughput, we see that EEA-based forwarding gives higher throughputs at some of the the packet generation probabilities than the good-link protocol. EE-based forwarding performs worse while the primary 6/3 forwarding protocol is significantly worse than the other three forwarding

protocols. EE-based forwarding does give the lowest end-to-end delays though its end-to-end success probabilities are also lower than those for EEA-based forwarding and the good-link protocol. When the signal-to-noise ratio is 14.0 dB (the bit error rate is 1.4×10^{-3}), the EEA-based forwarding protocol gives about the same throughput values as the good-link protocol, (see Figure 8). When the signal-to-noise radio is large, either the side information or the information about lack of acknowledgements provides a reasonable indication of the link quality: either the link is bad if the jammer is present, or the link is good. But, for lower signal-to-noise ratios it is more difficult to determine if a failure to receive an acknowledgement is due to jamming or to noise alone, because there is a higher probability that a packet forwarded on a link that is not jammed will be unsuccessful. In this case, the side information is much more reliable, because it provides an indication about the level of interference on the link. We also examined the forwarding protocols with ρ=0.55 and ρ=0.2 for both signal-to-noise ratios, and similar observations were made. For the higher signal-to-noise ratio, EEA-based forwarding and the good-link protocol perform about the same. For the lower signal-to-noise ratio, EEA-based forwarding gives slightly higher throughputs than the good-link protocol. The differences are slightly larger for ρ=0.55 and slightly less for ρ=0.2, reflecting that an alternate route around the jammed radio is more valuable when the fraction of the band jammed is larger.

We have also examined the forwarding protocols when only one jammer is present. The good-link protocol performs better than the primary 6/3 forwarding protocol, and EEA-based forwarding performs approximately in between. The differences between the forwarding protocols are the largest when ρ=0.55, while the forwarding protocols all perform about the same when ρ=0.2. When ρ=0.55 nearly all the packets forwarded to a jammed radio will be unsuccessful, so just the lack of an acknowledgement is sufficient to determine if a link is jammed. Since there is only one jammer, any attempt at using an alternate route will likely be successful. Forwarding packets in a network with only one jammer is not as complex and does not fully demonstrate the capability of the side information in choosing the best links.

2.4.2 Results for routing protocols

For the investigation of the routing protocols the jammer period was increased to 500 packet time intervals. Of course the routing tables are not fixed during this phase of the investigation. New routes are added when a PROP is received, since a radio can determine if the source of the PROP can provide a better route to the destination than one of the routes the radio currently has stored. The results for the routing protocols for partial-band jamming with ρ=0.2 are show in Figures 9–14. In Figure 9, the EEA metric has higher throughputs than the other metrics when the packet generation probability becomes large. For smaller values of p, all the routing metrics perform about the same. The CA metric has higher throughputs than the EE metric, showing that the information from the lack of acknowledgements is an important part of the metric. From Figures 12–14, tier routing performs much worse than even the LP metric (as we know from our previous work) [11,13,15]. From Figure 10, the metrics with the higher throughputs, in general, have the lower delays. Similar observations are made about the end-to-end probability of success. We also examined the EEA metric when the first five (instead of three) transmissions are made on the primary link. This modification had almost no effect on the performance of the metric, except that the end-to-end delay was slightly higher at all the generation probabilities.

The results for when ρ=0.4 are shown in Figures 15–20. At the lower generation probabilities, the routing metrics and tier routing have throughput values that are very close. At higher generation probabilities the EEA metric has higher throughputs while the other metrics all perform about the same. The LP metric has throughputs that are the same or higher than the CA metric, unlike the case when ρ=0.2. Modifying the EEA metric to make the first five transmissions attempts on the primary route resulted in throughput values that are generally higher than when only three attempts are made on the primary link, but, the end-to-end delays are also higher, see Figures 21-22. When ρ=0.4, the side information is able to provide a better indication of the link quality than when ρ=0.2. So, allowing the routing protocol to rely more heavily on the side information by not using the secondary route until the last transmission attempt increases the throughput.

We have also examined the routing protocols when only one jammer is present. The EEA metric, CA metric, and LP metric all perform approximately the same under various values for ρ. Further comparisons were made when the Markov chain for the multiple-access interference was modified. States 2 and 6 were removed and the transition probabilities were reduced to 0.2. These modifications did not change the performance significantly for any of the routing protocols when using either one or two jammers. A investigation was also made when no additional multiple-access interference was included (i.e., the Markov chains were fixed in the zero state). The performance results were very similar to the case when the extra multiple-access interference was included. This suggests that the conclusions drawn about the routing protocols are fairly independent of the multiple-access model, but depend heavily on the partial-band interference model.

The EEA metric, which modifies the EE metric to increment the resistance when an acknowledgment is not received, significantly improves the performance. A similar modification to the LP metric did improve the performance of the LP metric but it did not match the performance of the EEA metric. The LP metric assigns a much larger resistance to a radio that is jammed than to a radio that is not jammed, in effect eliminating the jammed radio from the network. The relative difference between resistance values under the EEA metric is not as large so that the jammed radios are still considered for some routes. The disappointing performance of the LP metric is especially evident when ρ=0.2, since at this level of partial-band interference the jammed radio can still receive some of the packets forwarded to it. By including the jammed radio in some routes, the neighbor radios can discover more quickly when the jammer changes locations. So, while the side information used for the LP metric is based on exact knowledge of the interference environment, the metric is not the most effective way to use that information.

From these results we can conclude that the side information provided by the decoder about the number of errors and erasures in addition to the information about the lack of acknowledgment transmissions can be used to provide a very effective metric for LRR. The benefits of the metric are more evident in a fairly complex network, in which it is important to choose a route based on

criteria other than just the shortest distance. The side information is effective in choosing routes that avoid the jammer, because the resistance calculated from the side information is larger for radios that are jammed. The acknowledgement information increases the resistance values that have not been update recently, providing a mechanism for eliminating outdated routing information.

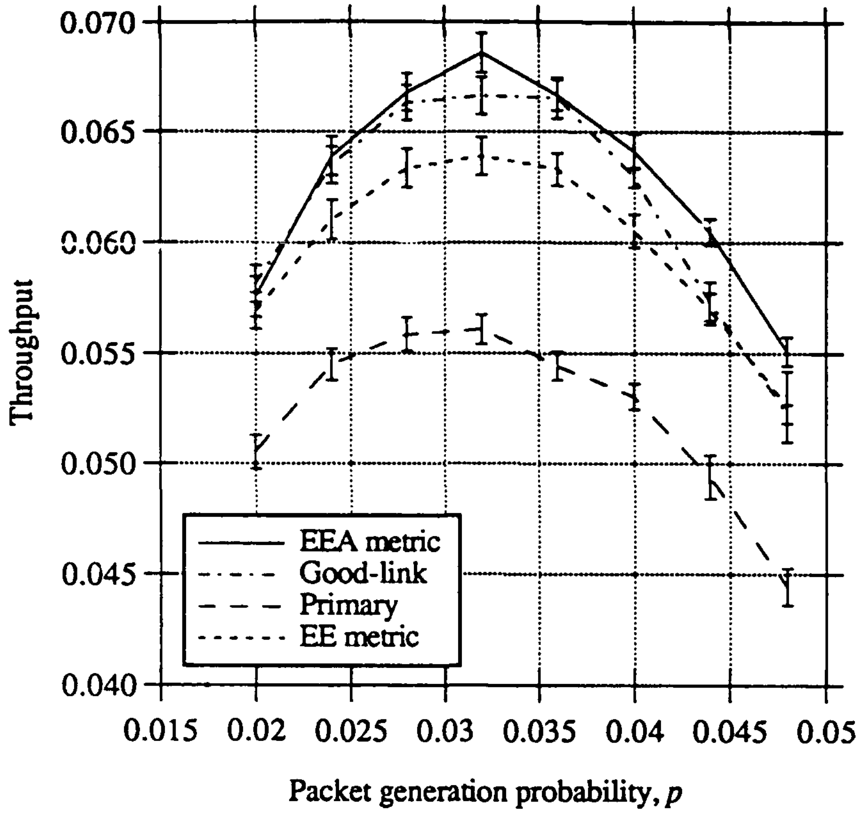

Figure 5. Throughput for forwarding protocols with ρ=0.4 and E_b/N_0=13 dB.

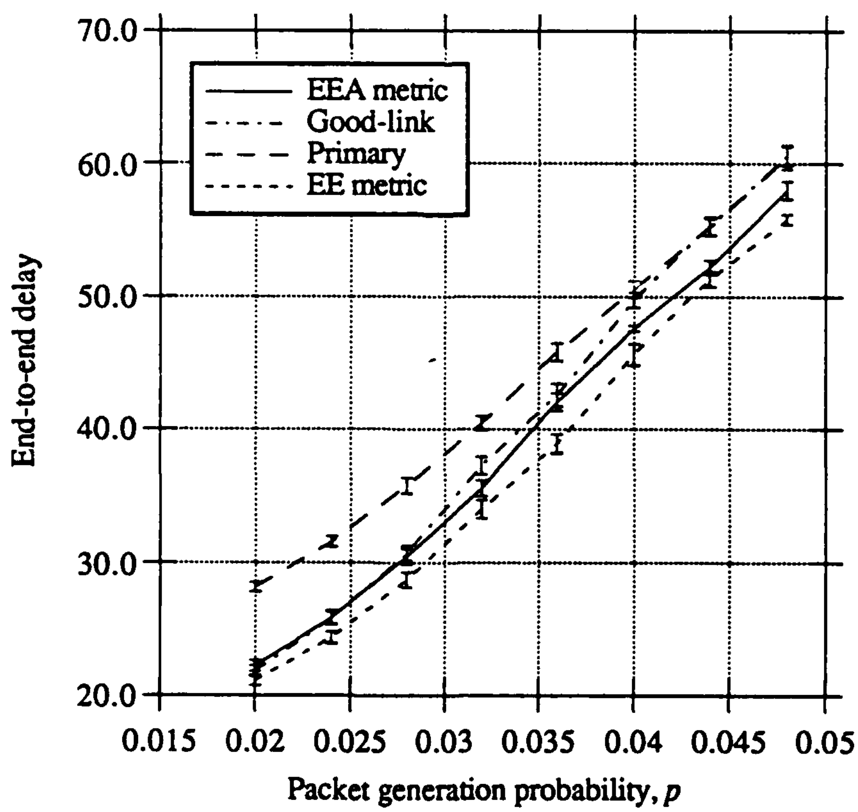

Figure 6. Delay for forwarding protocols with ρ=0.4 and E_b/N_0=13 dB.

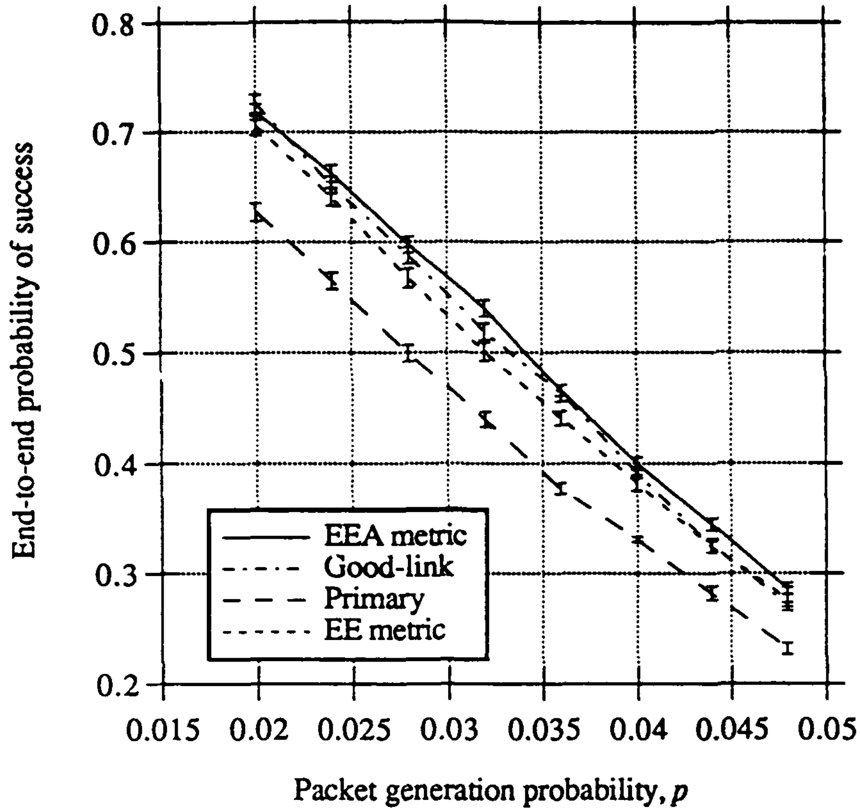

Figure 7. Probability of success for forwarding protocols with ρ=0.4 and E_b/N_0=13 dB.

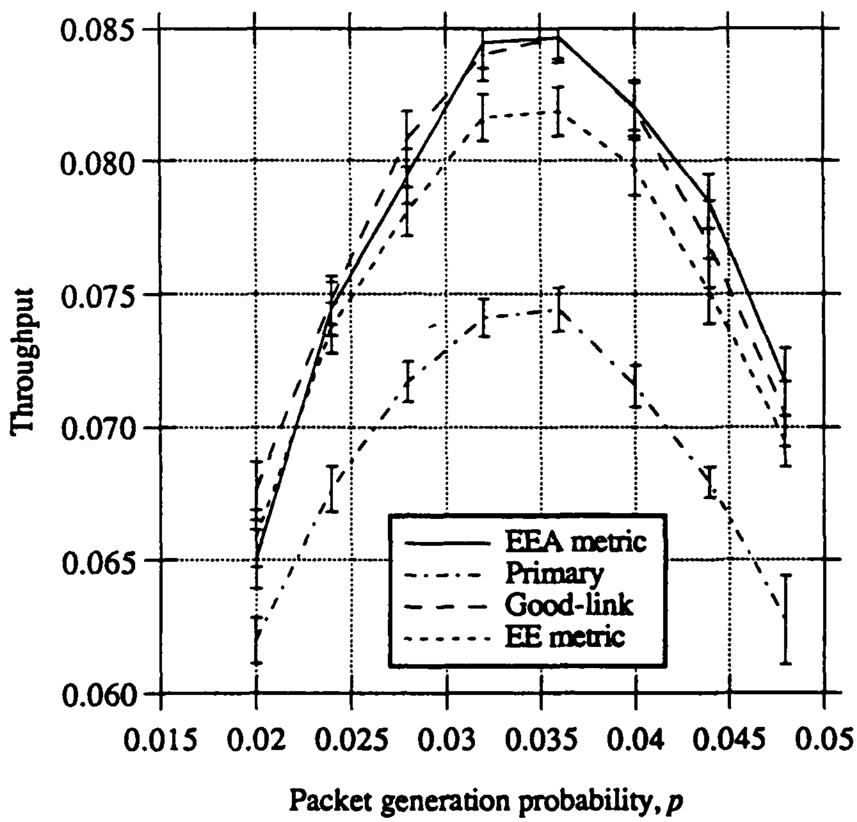

Figure 8. Throughput for forwarding protocols with ρ=0.4 and E_b/N_0=14 dB.

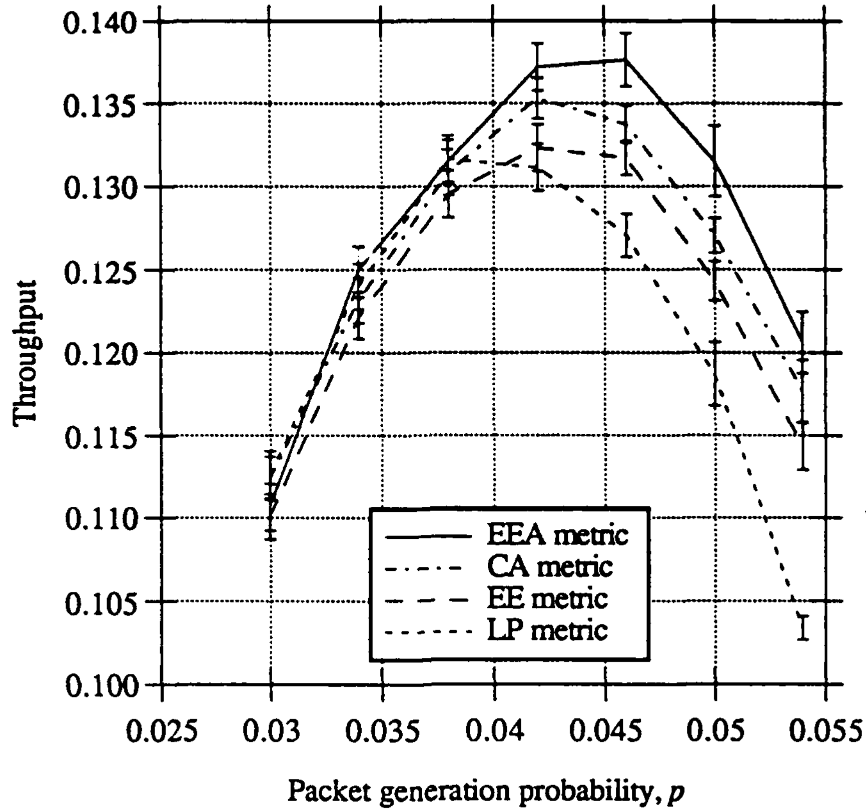

Figure 9. Throughput for routing protocols with ρ=0.2 and E_b/N_0=14 dB.

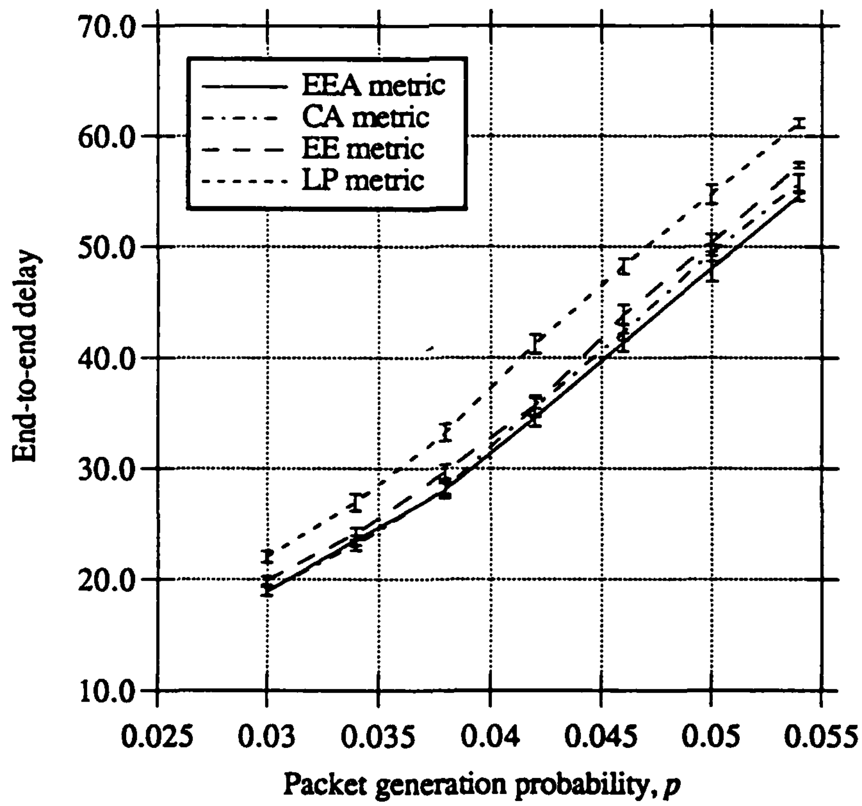

Figure 10. Delay for routing protocols with ρ=0.2 and E_b/N_0=14 dB.

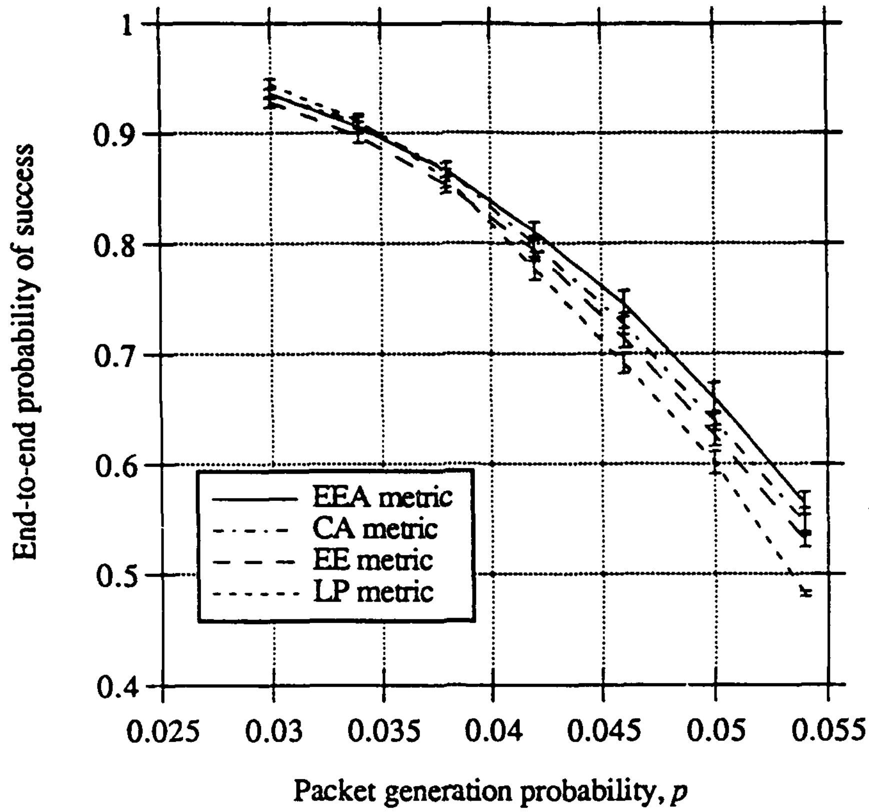

Figure 11. Probability of success for routing protocols with ρ=0.2 and E_b/N_0=14 dB.

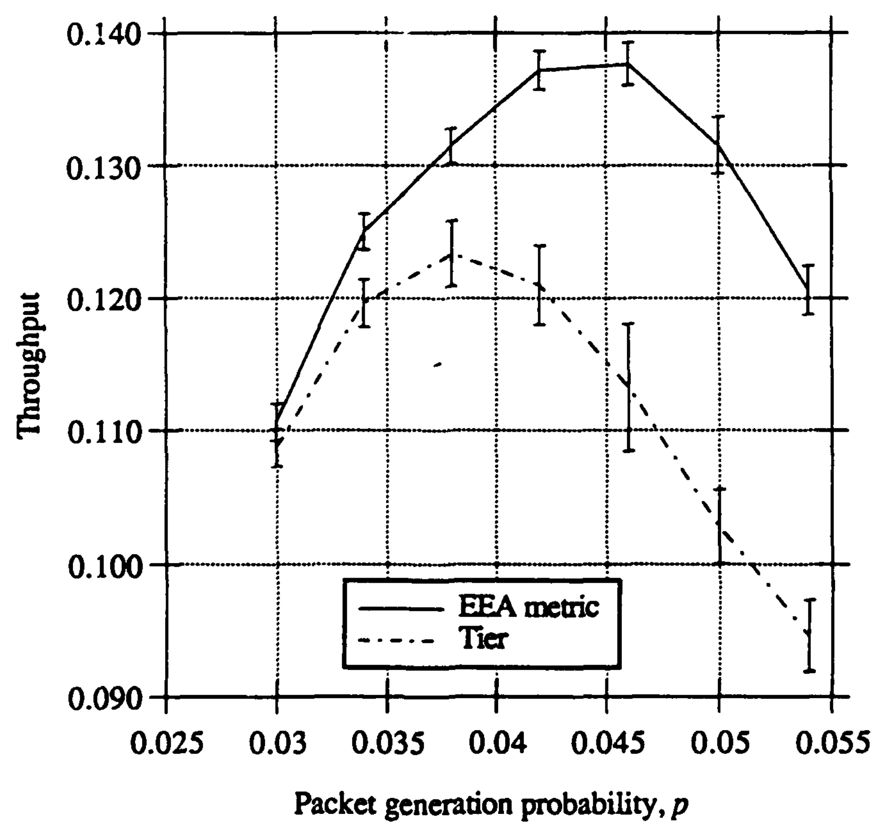

Figure 12. Throughput for tier routing and EEA metric with ρ=0.2 and E_b/N_0=14 dB.

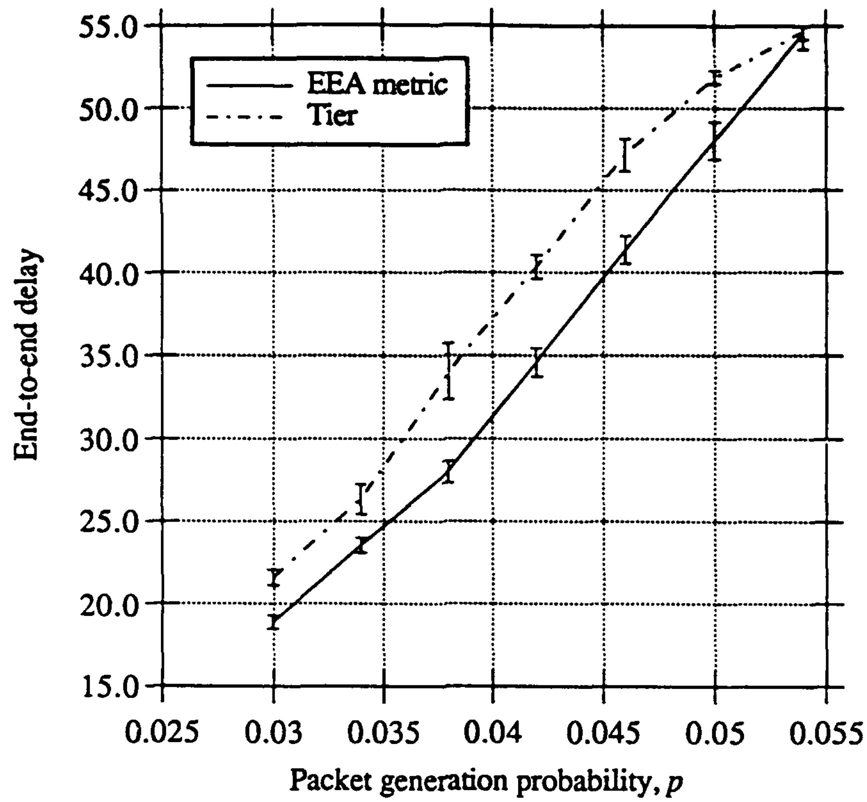

Figure 13. Delay for tier routing and EEA metric with ρ=0.2 and E_b/N_0=14 dB.

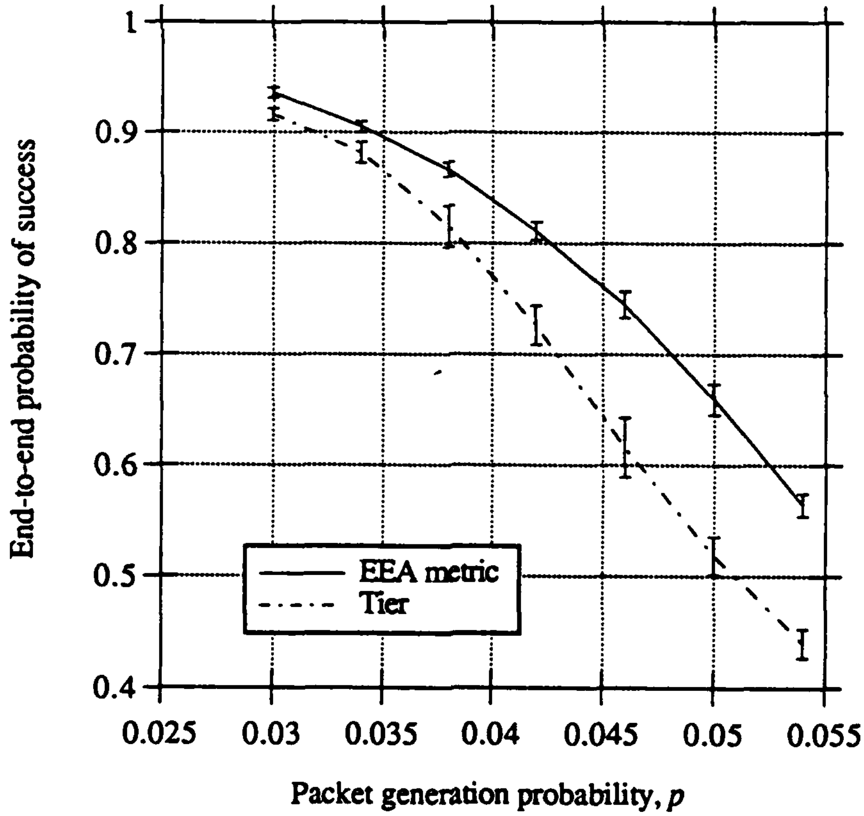

Figure 14. Success probability for tier routing and EEA metric with ρ=0.2 and E_b/N_0=14 dB.

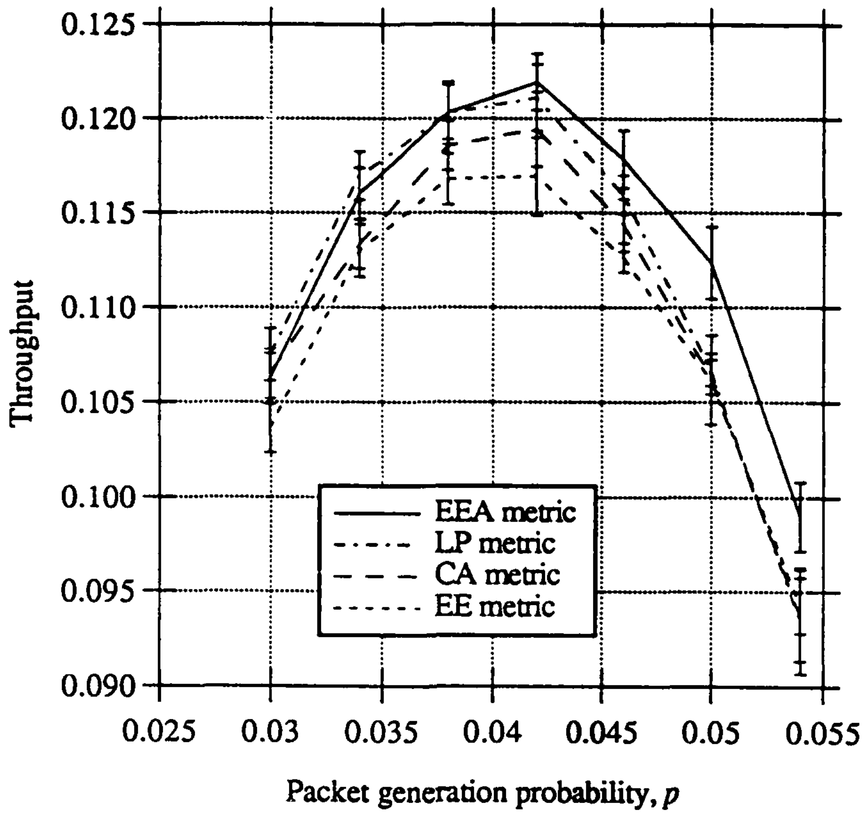

Figure 15. Throughput for routing protocols with ρ=0.4 and E_b/N_0=14 dB.

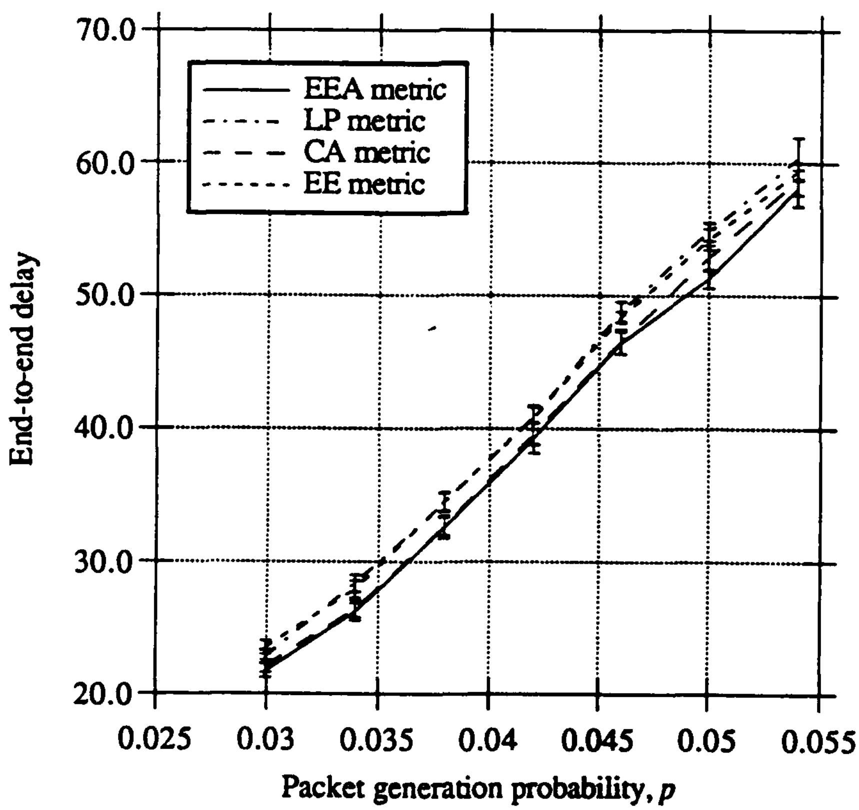

Figure 16. Delay for routing protocols with ρ=0.4 and E_b/N_0=14 dB.

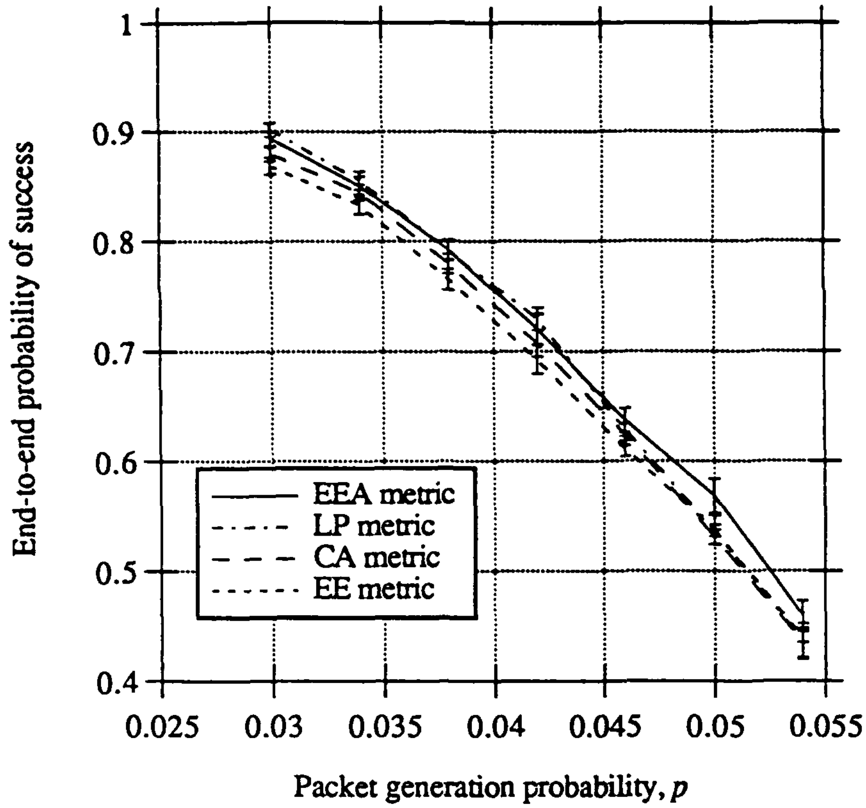

Figure 17. Probability of success for routing protocols with ρ=0.4 and E_b/N_0=14 dB.

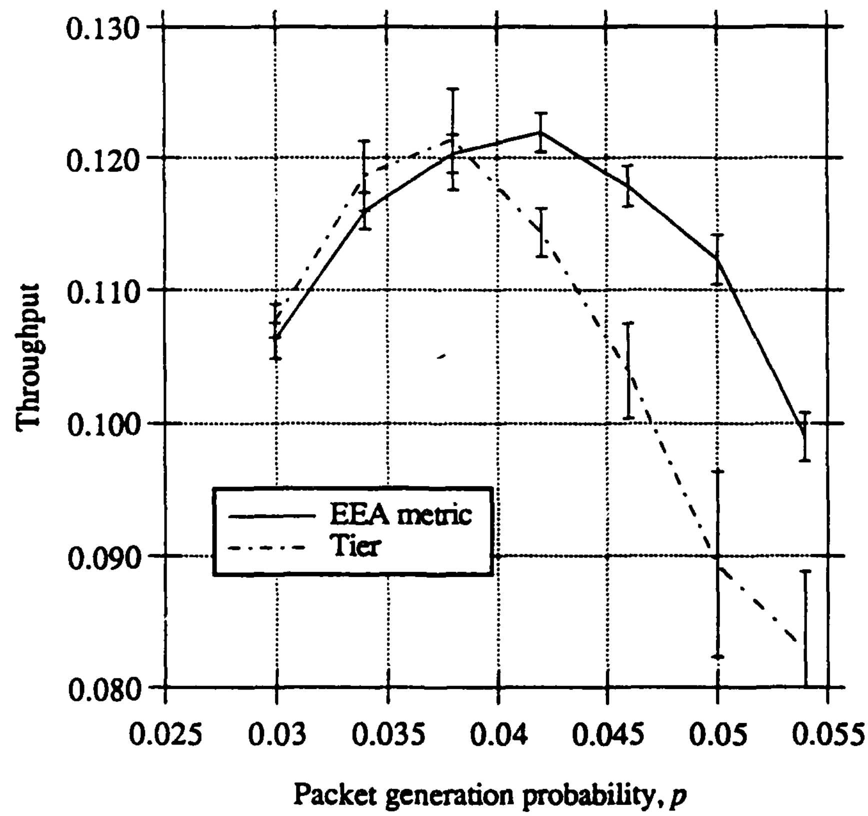

Figure 18. Throughput for tier routing and EEA metric with ρ=0.4 and E_b/N_0=14 dB.

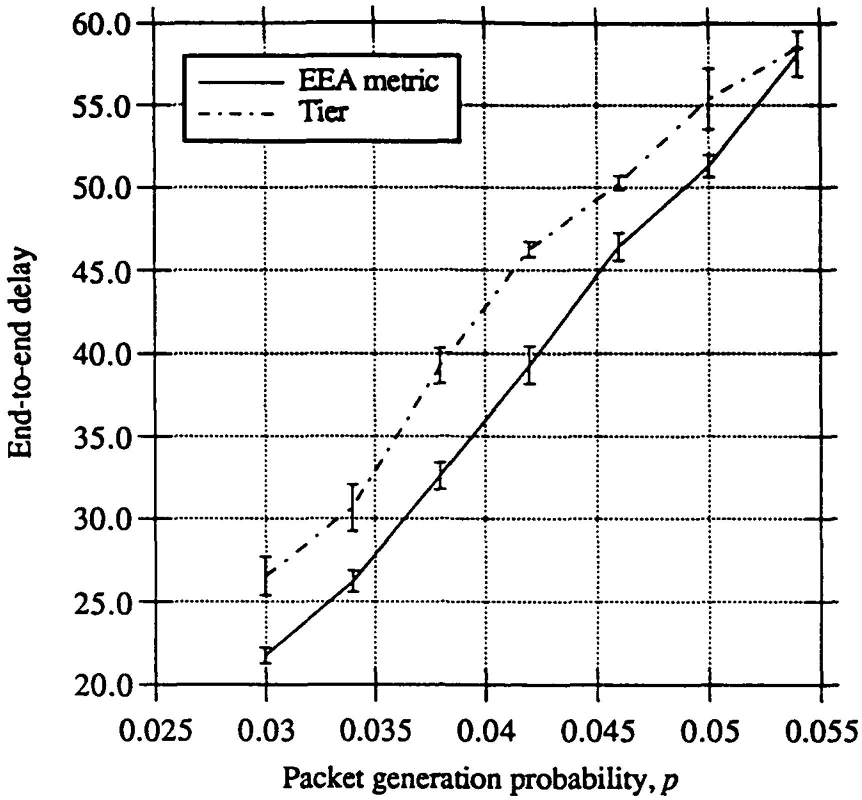

Figure 19. Delay for tier routing and EEA metric with ρ=0.4 and E_b/N_0=14 dB.

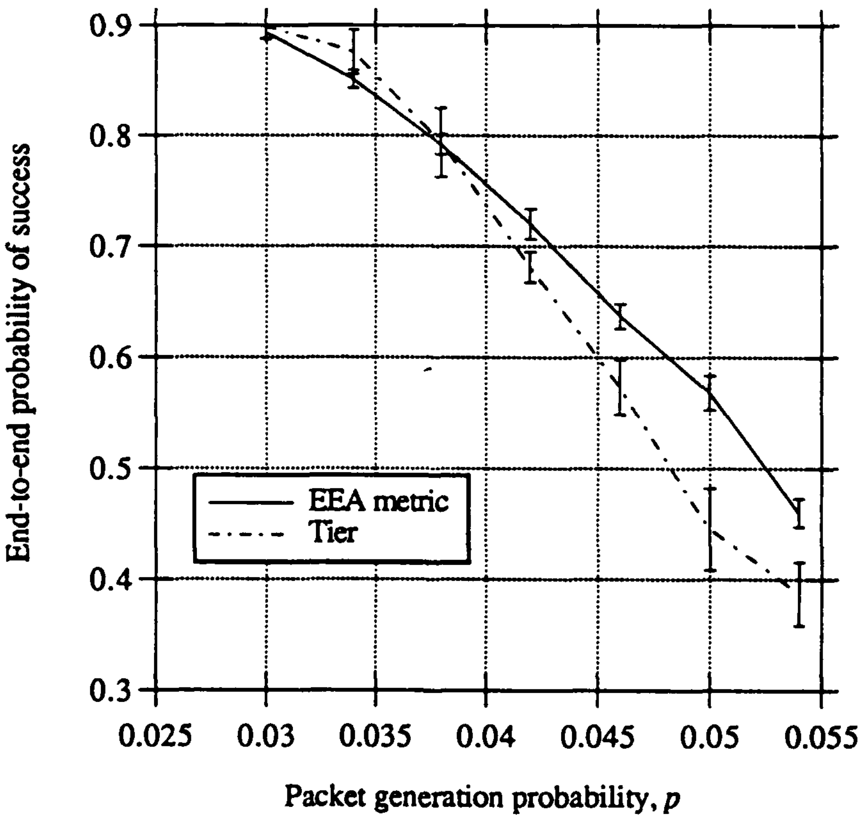

Figure 20. Probability of success for tier routing and EEA metric with ρ=0.4 and E_b/N_0=14 dB.

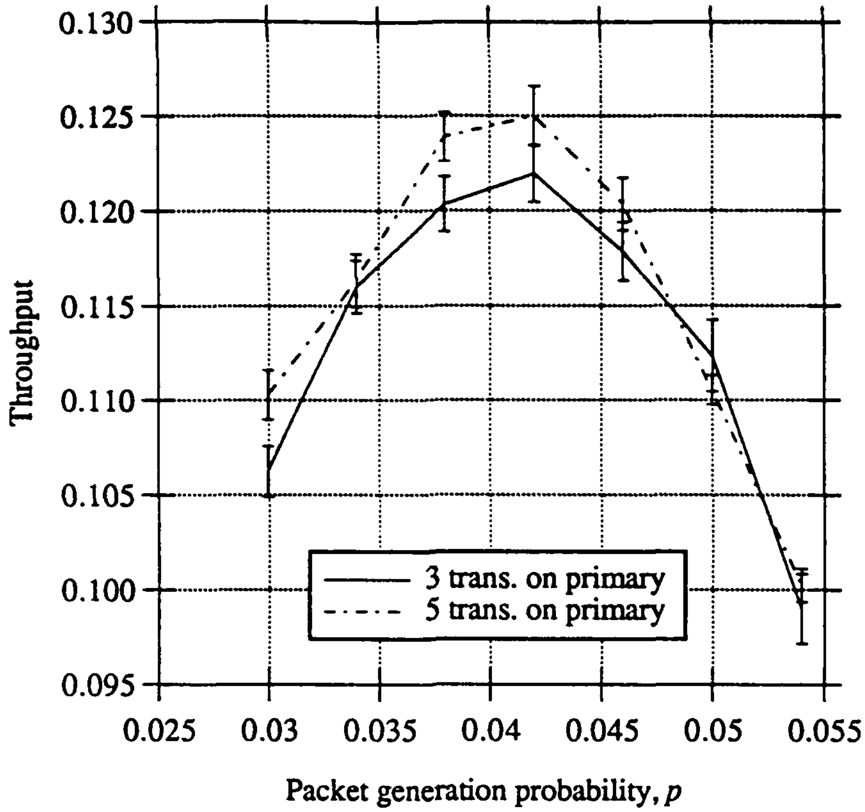

Figure 21. Throughput for routing protocols with 3 vs. 5 transmission attempts on primary link.

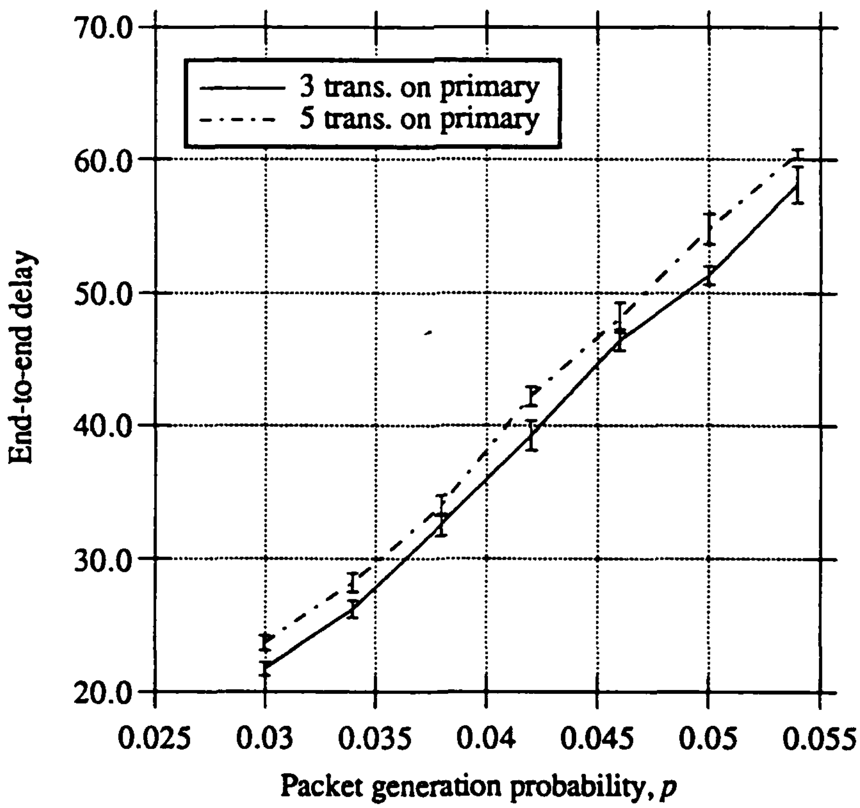

Figure 22. Delay for routing protocols with 3 vs. 5 transmission attempts on primary link.

3. References

[1] C. W. Baum and M. B. Pursley, "Erasure insertion via the ratio-threshold test in frequency-hop multiple-access radio networks with partial-band interference," *1990 IEEE Military Communications Conference Record*, vol. 2, pp. 603-607, Oct. 1990.

[2] K. G. Castor and W. E. Stark, "Performance of diversity/Reed-Solomon coded SSFH communications with errors/erasures via ratio thresholding," *Allerton Communication, Control and Computing Conference Record*, pp. 869-877, Oct. 1985.

[3] K. G. Castor and W. E. Stark, "Parallel decoding of diversity/Reed-Solomon coded SSFH communications with repetition thresholding," *Proceedings of the 1986 Conference on Information Sciences and Systems*, (Princeton University), pp. 75-80.

[4] J. Jubin, "Current packet radio network protocols," *IEEE INFOCOM Proc.*, pp. 86–92, March 1985.

[5] J. Jubin and J. Tornow, "The DARPA packet radio network," *Proc. IEEE*, vol. 75, pp. 21-32, Jan. 1987.

[6] A.W. Lam and D.V. Sarwate, "A comparison of two methods for generation of side information in frequency-hop spread-spectrum multiple-access communications," *Proceedings of the 1987 Conference on Information Sciences and Systems*, (Johns Hopkins University), pp. 426-431, March 1987.

[7] C. D. Frank and M. B. Pursley, "On the statistical dependence of hits in frequency-hop multiple access," *IEEE Trans. on Commun.*, pp. 1483-1494, Sept. 1990.

[8] M. B. Pursley, "Frequency-hop transmission for satellite packet switching and terrestrial packet radio networks," *IEEE Trans. Inform. Th.*, vol. IT-32, pp. 652-667, Sept. 1986.

[9] M. B. Pursley, "Packet error probabilities in frequency-hop radio networks—Coping with statistical dependence and noisy side information," *IEEE Global Telecommunications Conference Record*, Vol. 1, pp. 165-170, December 1986.

[10] M. B. Pursley, "Tradeoffs between side information and code rate in slow-frequency-hop packet radio networks," *1987 IEEE International Conference on Communications Conference Record*, pp. 947-952.

[11] M. B. Pursley and H. B. Russell, "Investigation of adaptive protocols for spread-spectrum packet radio networks," Final Report for U.S. Army Contract No. DAAL03-88-C-0022, July 1989.

[12] M. B. Pursley and H. B. Russell, "Adaptive forwarding and routing in frequency-hop spread-spectrum packet radio networks with partial-band jamming," *1989 IEEE Military Communications Conference Record*, vol. 1, pp.230-234, October 1989.

[13] M. B. Pursley and H. B. Russell, "Routing in frequency-hop packet radio networks with partial-band jamming," *Proceedings of the Tactical Communications Conference*, Fort Wayne, Indiana, vol. 1, pp. 117-126 April 24-26, 1990.

[14] M. B. Pursley and H. B. Russell, "Adaptive forwarding in frequency-hop spread-spectrum packet radio networks with partial-band jamming," submitted to *IEEE Transactions on Communications*.

[15] M. B. Pursley and H. B. Russell, "Routing in frequency-hop packet radio networks with partial-band jamming," submitted to *IEEE Transactions on Communications*.

[16] M. B. Pursley and W. E. Stark, "Performance of Reed-Solomon coded frequency-hop spread-spectrum communications in partial-band interference," *IEEE Transactions on Communications*, vol. COM-33, pp. 767-774, Aug. 1985.

[17] A. J. Viterbi, "A robust ratio-threshold technique to mitigate tone and partial band jamming in coded MFSK systems," *IEEE Military Communications Conference Record*, pp. 22.4.1-5, October 1982.